DOT HS-805 696

:VELOPMENT OF THE DEPLOY COMPUTER MATH MODEL .JR THE INVESTIGATION OF VARIOUS AIRBAG AND CRASH PARAMETERS ON THE OUT-OF-POSITION OCCUPANT

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16. Abstract This program is based upon a previous program known as "Bagslap" and is expanded and improved over the original version. A chest surface mass has been added. The bag deployment algorithm improved, and additional output provided.

The program computes the interaction of a normally seated or an out of position passenger with a deploying airbag in a crash or non-crash situation. The user specifies certain variables such as bag shape and volume, bag weight, vent area, vent actuation pressure, passenger weight, weight of chest surface, impact velocity, chest width, gas flow parameters, chest surface and chest overall force-displacement parameters, crash pulse and a few other parameters.

The program then computes the dynamics of the interaction of the deploying airbag and the passenger. Typical output would be the accelerations of the passenger, The airbag and both chest masses; the velocity of the vehicle, passenger, airbag, and the masses; the displacement of the vehicle, airbag and the chest masses; as well as the other parameters of interest such as chest penetration of the airbag, Pressure in the bag, volume of the bag, mass rate of flow of gas exiting the bag, and the chest forces.

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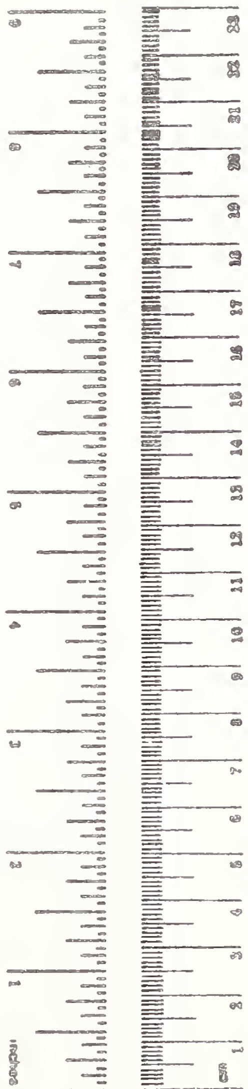
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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List of Illustrations

Note : Tapes of the
DEPLOY Computer Program
are available through
NHTSA/Office of Passenger
Vehicle Research.

Please make initial inquiries
to that office.

ABSTRACT

A computerized mathematical model (DEPLOY) has been developed which predicts the response of a forward positioned occupant's chest interacting with a deploying air bag. In addition, this computer program predicts the chest response of normally seated occupants, permitting the model to be used in a comprehensive parameter study of air bag design factors including the competing protection requirements for normally seated adults and forward positioned children. Development of this model along with further development of refined and expanded models of this type will permit a generalized systems approach at air bag parameter design. This approach is essential considering the large numbers of parameters to be investigated in any air bag development program and the associated substantial expense in exhaustively establishing design relationships and limits using laboratory testing with anthropomorphic test devices or animals.

1.0 INTRODUCTION

The continuing evolution of air cushion technology requires more powerful predictive tools to represent the thermodynamic and mechanical relationships which govern not only the dynamics of the restraint phase but also of the deployment phase dynamics where there is some finite chance that an occupant, positioned forward at the time of deployment, will interact with the bag.

The development of the DEPLOY computerized mathematical model is a first step in developing such tools which can be used in a comprehensive systems analysis approach to air cushion analysis and design. The benefits of having a model which predicts the primary dynamic modes of an air bag in both the restraint and deploying modes is that both design and analysis can be conducted in an atmosphere of much greater confidence in the performance evaluation results. The governing equations and principles will, in effect, interpolate between the data points to predict the performance of the system at points where, due to finite testing resources, test results are not available. Additionally, even when a full matrix of all feasible test conditions are run, the unavoidable variations in surrogates and other test conditions can inject unacceptable variations into the test results either in terms of meeting compliance requirements or, in defending the performance of the system in any product liability actions. These uncertainties can mask the location of the idealized performance curve predicted by the fundamental physical principles governing the dynamics being investigated and, if enough repeat tests cannot be run, the performance curve cannot be located by regression means either. This reasoning is at the core of the impetus to embark on the investigative path on which DEPLOY is only the first milestone.

2.0 OBJECTIVES AND APPROACH

2.1 Objectives

The objectives of this effort then were to:

1. Derive a computerized math model capable of accurately predicting the air bag deployment and restraint processes and the resulting dynamic responses of both normally seated and forward positioned occupants.

2. Exercise the computer model so developed to perform a sensitivity analysis on the many parameters which might influence the response of the forward positioned occupant. The results of this sensitivity analysis are to show the influence of these parameters on the occupant responses and the trends in variation over the full range of values which are observed in current design practice.

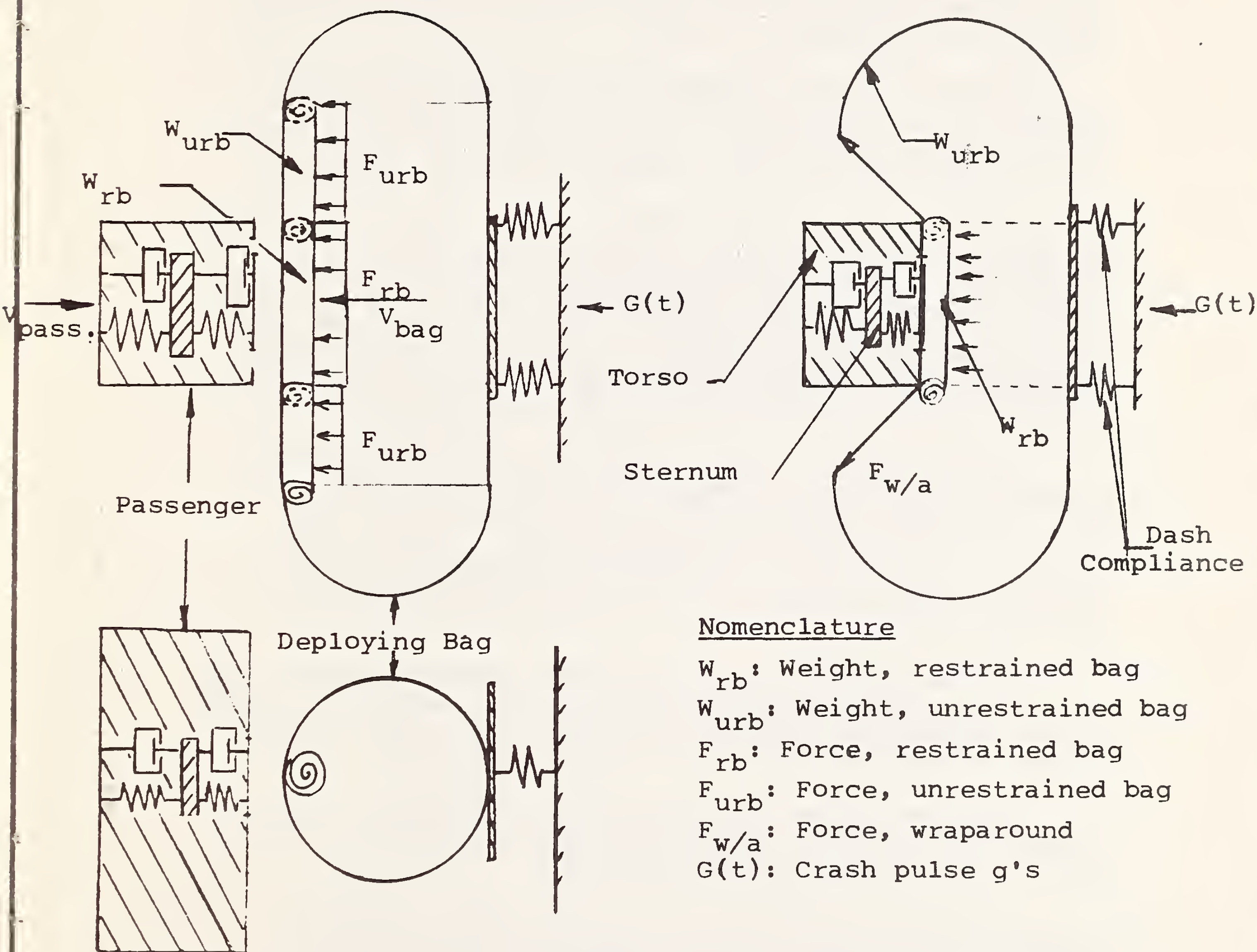
3. To use the DEPLOY program in a systems analysis approach at developing several air bag/inflator/module concepts which considers the full range of realistic values of the design parameters being studied and to minimize the injury potential of the collective influences of these influential design parameters. Directions in hardware development should be apparent from the results of this systems approach.

2.2 Approach

The DEPLOY model is looked upon as the first step in a continuing evolvement of mathematical models to represent the physical system of an air bag deploying and restraining an occupant. The DEPLOY model is a one-dimensional representation of the vehicle occupant in which the occupant is constrained to move only in the horizontal fore-aft direction directly toward or away from the deploying air bag. As such, no articulation is considered in this model. The air bag is modeled in three dimensions but in this version, the occupant's chest can only respond in the x-direction. Figure 1 shows schematically the math model for the DEPLOY program.

The DEPLOY model was inspired by, and based in part on, a previous program called BAGSLAP but because of evolving needs and information concerning the dynamics of deploying airbags, it was necessary to take a fresh approach at the requirements for such a computer program. The differences between DEPLOY and BAGSLAP are as follows:

SCHEMATIC OF "DEPLOY" COMPUTER MODEL



Nomenclature

W_{rb}: Weight, restrained bag
W_{urb}: Weight, unrestrained bag
F_{rb}: Force, restrained bag
F_{urb}: Force, unrestrained bag
$F_{w/a}$: Force, wraparound
G(t): Crash pulse g's

Figure 1.

The BAGSLAP program had been written using part of one program (ABAG 19) to give results during the "waterwing" phase of air bag deployment but used another air bag algorithum to yield results during the "bagslap" phase. A discontinuity was present as the program switched from the bagslap phase to the catapult phase of deployment. Further compounding the problem was that the time at which the switch occured was required input by the user. There was no way for the user to know - apriori - when this might happen and, consequently, the results could vary considerably just based upon the input of the time catapult was to begin. Even if it was known when this would occur, a large discontinuity in output values was observed as the changeover occured.

A second area where the BAGSLAP program was judged to be inadequate for this study was in the values selected for output. In order to gain insight it was necessary to have more output concerning the details of bag deployment and chest response.

For these reasons the BAGSLAP program was extensively modified and expanded to provide the information needed for the study. The discontinuity described above was eliminated by using the same general air bag algorithum throughout the event. In order to gain more information on chest response, a second chest mass was added in series with the main chest mass. This second mass represents the sternum and will help in describing the details of total chest response, especially during the very complex bagslap phase.

This two-mass chest model included the spring rates and damping ratios between the sternum mass and the spinal main body mass. Provisions were also made for a seperate analysis if the child's chest were to bottom out on the dash. In this event, computation of g levels were modified accordingly so that either bagslap or catapult would continue after the chest had rebounded away from the dash.

The force computations during bagslap were modified to be more accurate by including wraparound forces and increasing the accuracy of the chest contact calculation. Further, the amount of output describing the airbag deployment process was doubled.

The resulting computer program was named "DEPLOY." The new designation was made to eliminate confusion for users who might be using either one or both of the programs.

Fundamental to developing any type of computer program to predict the interaction dynamics of air bags with forward positioned occupants, is the requirement that this same program should also accurately predict the responses of normally seated adult occupants restrained by the air bag in car crash conditions. Any such model should provide guidance in parameter studies for both the forward positioned occupant and the normally seated adult

because the ultimate design will have to consider the extensive exposure of the normally seated adult along with the small but finite exposure of an out-of-position child. It is highly desirable, and a goal of this effort, to take a first step at developing the analytical tools which will aid the designer in making informed and objective decisions concerning any competing factors in these two very different performance requirements.

In any computer approach to investigating how various parameters interact to produce a result, the investigator must have some informed ideas on the types of designs he wishes to investigate. Without this, the analysis would take inordinate amounts of time and effort to complete as one proceeded through each independent variable on a one by one basis and then varying the dependent variable through the range of interest. Not only would this approach take a great deal of time, but it also would result in voluminous output which would confuse the relationships being sought. This approach, not withstanding being generally undesireable, is clearly beyond the scope of this study.

To establish a firm experimental basis for this modeling effort a brainstorming session was held with a number of experts in the field in which many approaches were generated and discussed. From this session came several promising methods of reducing the injury potential to the forward positioned occupant. Some were of a nature that would lend themselves to computer simulation and therefore were pursued in this modeling effort. Other concepts were more immediately tractable to experimental investigation and were assigned as such.

The areas which were identified for computer analysis were:

- Inflator mass flow tailoring
- Staged inflation
- Chest-to-dash spacing
- Air bag shape and volume
- Air bag fabric mass
- Aspiration and gas dump valves
- Interrelationships of the above factors.

In addition, the program is readily adaptable to investigating cover mass effects but the constraints on this effort did not permit a parameter sensitivity analysis on this factor.

The approach here was to investigate each of these areas individually in order to assess their relative potential for injury reduction and, just as importantly, to determine the effects of these combined parameters and how they interact to determine the responses of the forward positioned occupants, particularly children. This would be a first attempt at a systems approach to considering the design factors for air bags and would give vastly greater confidence in predicting the performance of air bags over the full range of parameters which may be determined by design or encountered in service. Thus, the major factors and their interralationships will be identified so that design efforts can be concentrated in these areas.

The crash environment selected for this study was based upon the Chevrolet Citation's performance in a frontal barrier test at 30 mph. It was thought that the GM X-Body cars would be representative of vehicles that would be manufactured for the next decade. The DEPLOY program is readily adapatable to analyzing other crash speeds and conditions.

3.0 COMPUTER PROGRAM DESCRIPTION AND VALIDATION

The DEPLOY program is based in large degree on the already existing BAGSLAP program with modifications and additions as described previously, and accordingly has certain features common to BAGSLAP. These common features include that DEPLOY is also written in the BASIC computer language and is a one-dimensional simulation of the vehicle occupant in which the occupant is constrained to move only in a horizontal plane directly toward or away from the deploying airbag. As such, no articulation of the occupant is considered (see Figure 1).

However, unlike the BAGSLAP model, a second chest mass has been added to DEPLOY in order to provide information on how the sternum responds during the bagslap portion of the event. Later, during the catapult phase, the lighter sternum and the main body mass are assumed to be locked together and exhibit common g levels.

In the original BAGSLAP version, wraparound forces were not considered during the bagslap phase. In addition, an approximation was made that the total bag front in contact with the child was always the instantaneous diameter of the deploying airbag. In writing the DEPLOY program, these approximations were eliminated. Experience has shown that these wraparound forces can play an important part in child response even during the bagslap phase and for this reason, wraparound was included in the DEPLOY model.

Further, rather than assume the whole bag diameter was reacting against the child at any particular instant, an input for the child's seated or standing height has been added and the exact length of bag in

contact with the child is computed in the progam. In this way there is no way in which the actual length of bag in contact with the child can be greater than his effective height. Further, the actual chord length of bag contact diameter is used rather than just the bag diameter.

Numerous other changes, most of which have been previously mentioned, were also made to the BAGSLAP program in order to render it responsive to the particular needs of this effort. Items not specifically mentioned are not required for the reader to understand the results given by DEPLOY. Tapes of the DEPLOY program are available through NWTSA, Office of Passenger Vehicle Research.

Appendix A contains a listing of the completed program, Appendix B contains the results of a typical computer run, Appendix C is the flowchart of the DEPLOY program and Appendix D is a line by line explanation of the data input values and formats. Let us now discuss a typical run in some detail so the program inputs, outputs and general capabilities can be understood.

When the user accesses the program, the computer will ask for a "deployment time." The program uses this input to trigger venting if the pressure conditions are satisfied (pressure greater than a specified amount - usually zero psig). For times less than this, venting is not allowed. Some judgement and knowledge of the system is presupposed here, but the time must be greater than the sensing time, usually falling between 15 to 30 msec after sensing. In physical terms, the deployment corresponds roughly to the time at which the pressure in the bag becomes positive for the second time (the first pressure spike is neglected since it is due only to getting the bag moving) or the bag is in firm contact with the chest or both. Thirty milliseconds have been used for most of the runs made with the program for this study.

Next the computer asks whether you want the full output of nineteen different output parameters printed or just the normal ten basic parameters. Once the user becomes familiar with the output, he can choose for himself which way to answer the question for the particular needs of the project.

Next the computer lists the main input variables which one might adjust in order to study various airbag systems, crash environments and child configurations. The input variables in the listed in Apendices B and D are:

1. Bag Diameter (the program assumes a cylindrical bag with hemisperical ends with the longitudinal axis perpendicular to the vehicle axis and at the same height as the occupant's center-of-mass), inches.
2. Total Bag Length, inches.
3. Bag Weight, ounces per square yard.
4. Vent Opening Pressure, psig.
5. Airbag initial pressure, psig.

6. Entering Gas Temperature, deg. F.
7. Dash Compliance, g's /inch.
8. Total Passenger Weight, lb.
9. Sternal Weight, lb.
10. Impact Velocity, fps.
11. Effective Height of Passenger, inches.
12. Width of Passenger's Chest, inches.
13. Initial Distance of the Passenger from the Dash, inches.
14. Dimensions of the Airbag Sleeve in which the Gas Generator is Located, inches.
15. Factor Used to Adjust the Effective Passenger Mass for Various Airbag Configurations.
16. Vent Coefficient (zero if vent area not dependent on any other variable such as pressure, time etc.).
17. Chest Mass Damping Coefficients (one for each mass).
18. Table of points Describing Gas Flow Profile, lb/sec vs time.
19. Table Describing Sternal Force-Deflection Relationship for Chest, lb. vs inches.
20. Table Describing Overall Force-Dleflection Relationship for chest, lb. vs inches.
21. Table Describing Vehicle Crash Pulse, g's vs time.

Parameters listed as output are (left to right across page):

Page 1

1. Elapsed Time, sec.
2. Passenger Chest G's (G).
3. Passenger Velocity, fps, (V).
4. Vehicle Velocity, fps, (VV).
5. Airbag Penetration, inches, (X).
6. Vehicle Crush, inches, (X1).
7. Airbag Pressure, psig, (P).
8. Airbag Volume, cubic inches, (VOL).
9. Rate of Gas Exiting Vent, lb/sec, (Q).
10. Passenger Sternal G's, (G6).

Page 2

11. Airbag G's, (B).
12. Airbag Velocity, (BV).
13. Airbag Over Ground Displacement, inches, (BD).
14. Sternal Overground Velocity, fps, (CSV).
15. Sternal Overground Displacement, inches, (CSD).
16. Force Applied to Sternum, lb., (CSF).
17. Airbag Diameter, inches, (D8).
18. Passenger Overground Displacement, inches, (PD).
19. Force Applied to Passenger Main Mass, lb., (PF).

3.1 ABAG 19 vs DEPLOY

Although the total time of this study was short and a large part of this time was necessarily spent in deriving the DEPLOY computer program, it was felt that it would be time well spent if some time was spent in validating the program. To this end, a comparison was made between the results generated by DEPLOY and those generated for an equivalent impact condition in ABAG 19, a program widely used by NHTSA and airbag designers for years. Since ABAG 19 does not have the capability to simulate the deploying airbag and the effect it has on the forward positioned occupant, the input of the more general DEPLOY program had to be adjusted to simulate the type of case for which ABAG 19 is normally used.

It was therefore chosen to simulate with both programs the case of a normally seated adult undergoing a crash situation in the crash environment of the Chevy Citation. Equivalent input was used in both simulations, i.e. the same airbag shape and volume, the same gas flow into the airbag, the same sensing and deployment time, the same passenger mass, etc.

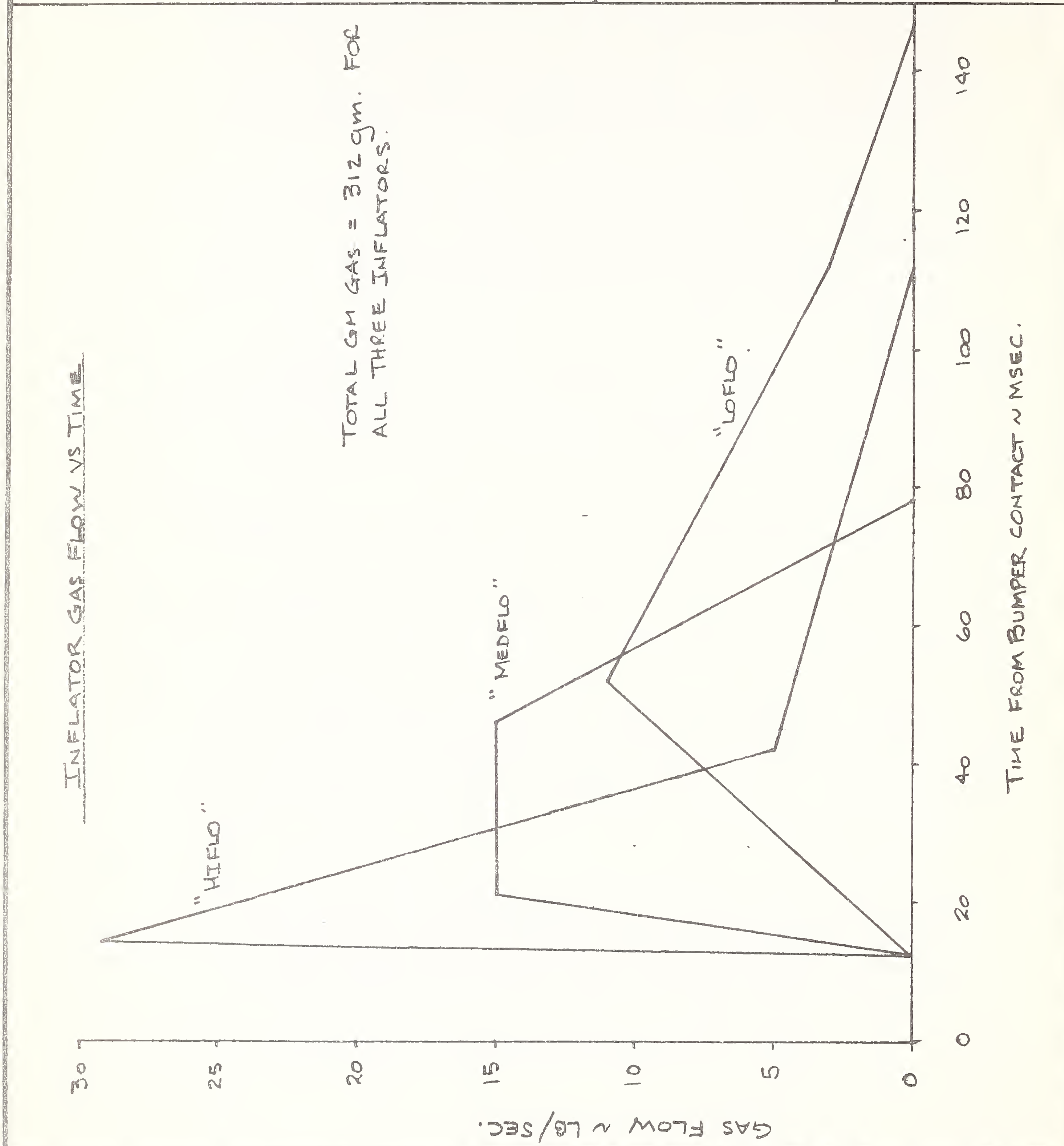
In order to obtain a comparison for more than a single condition, three widely different gas flow profiles were used in the simulations and a total of six computer runs were made - three with ABAG 19 and three with DEPLOY. The three gas flow profiles used in the simulations are the same ones used in the study reported in Section 4.0 and are shown by Figure 2.

Figure 3 shows the results of this comparison. In this figure, the computer predicted peak chest g's are compared for the two programs for each of the three gas flow profiles.

As can be seen from the figure, very good agreement was obtained despite the fact that the bag shape algorithms used in the two programs were different.

One area in which the results were somewhat different was in phasing. Due to the finite (not zero) mass of the airbag in the DEPLOY program and the fact that the whole airbag deployment process is modeled, it takes longer to reach the peak chest g's than in the ABAG 19 model. We feel that the results would match more closely in phasing if the deployment time of ABAG 19 were increased somewhat to compensate for this fact.

The comparison serves as a good general check on both programs; ABAG 19 which has been in use for some time and DEPLOY which is mainly new except for those parts that are still common to the BAGSLAP program. Further, the results of this comparison are sufficiently close to warrant using DEPLOY with a good degree of confidence in this study.



INFLATOR GAS FLOW VS TIME
TOTAL GM GAS = 312 gm. FOR ALL THREE INFLATORS.
"HIFLO"
"MEDFLO"
"LOFLO"
GAS FLOW ~ LB/SEC.
TIME FROM BUMPER CONTACT ~ MSEC.
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140

Figure 2.

PROJECT

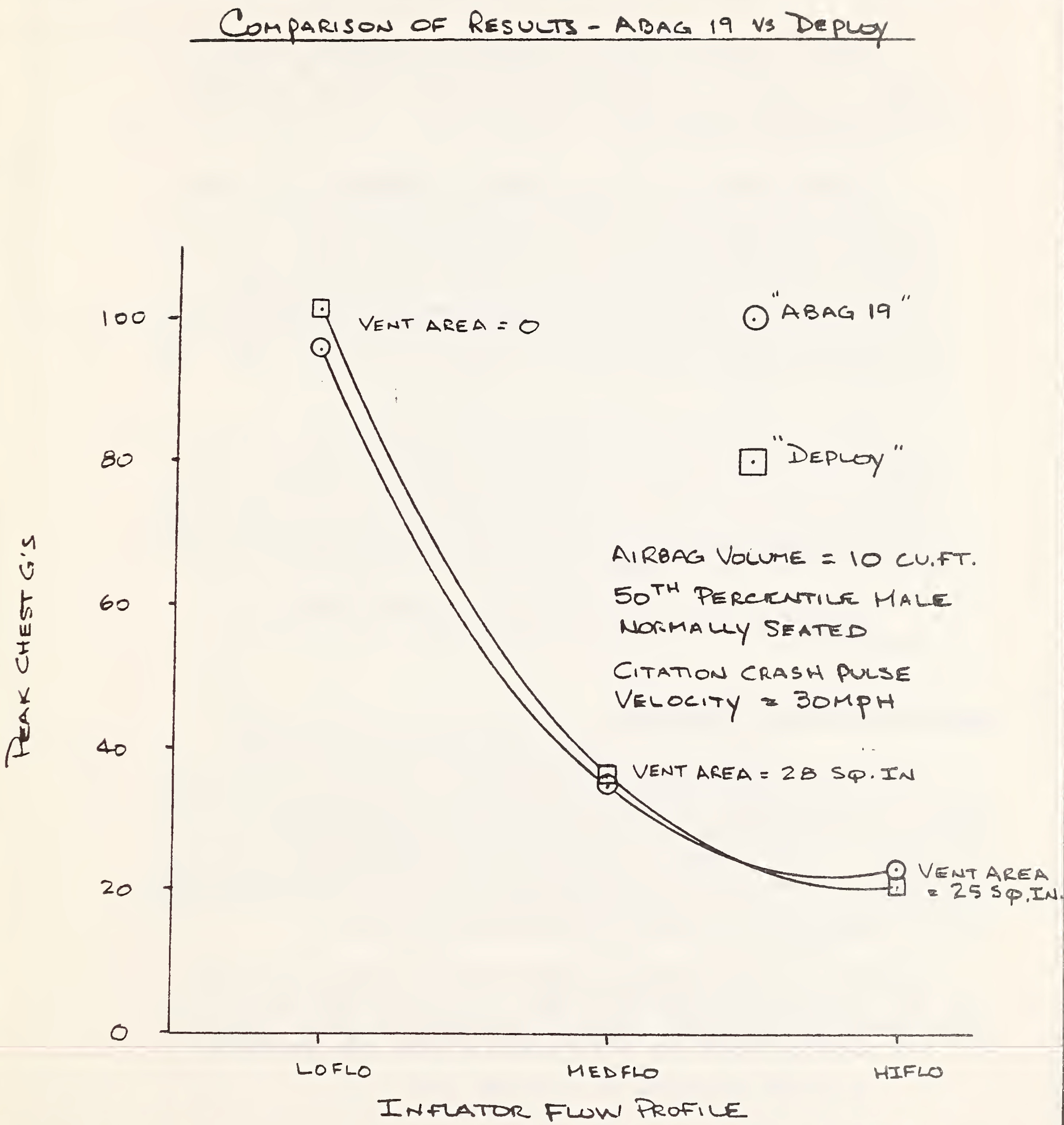


Figure 3.

3.2 Computer vs. Test Results

In order to further validate the DEPLOY computer program the results predicted by DEPLOY were compared with recent sled testing done with the forward positioned child by Minicars Inc.

Minicars Sled Run 1637 was selected as "typical" in that no unusual or otherwise unexplainable events occurred, the results seemed to be similar to other runs made under similar conditions, and the inflator used was the latest version of the one Minicars was using on the Small Car Airbag Program.

Minicars supplied the data needed for computer input such as the crash pulse, the 3 yr. old dummy chest parameters, the impact velocity, the sensing time, the airbag shape and volume, the initial distance of the dummy chest from the dash, the inflator gas flow rate, etc. Fitzpatrick Engineering prepared this data from Sled Run 1637 for computer input and then ran the program varying the vent area (which was essentially unknown since the airbag venting occurs not only through the vent, but also through the airbag seams) until the best match with test data was obtained.

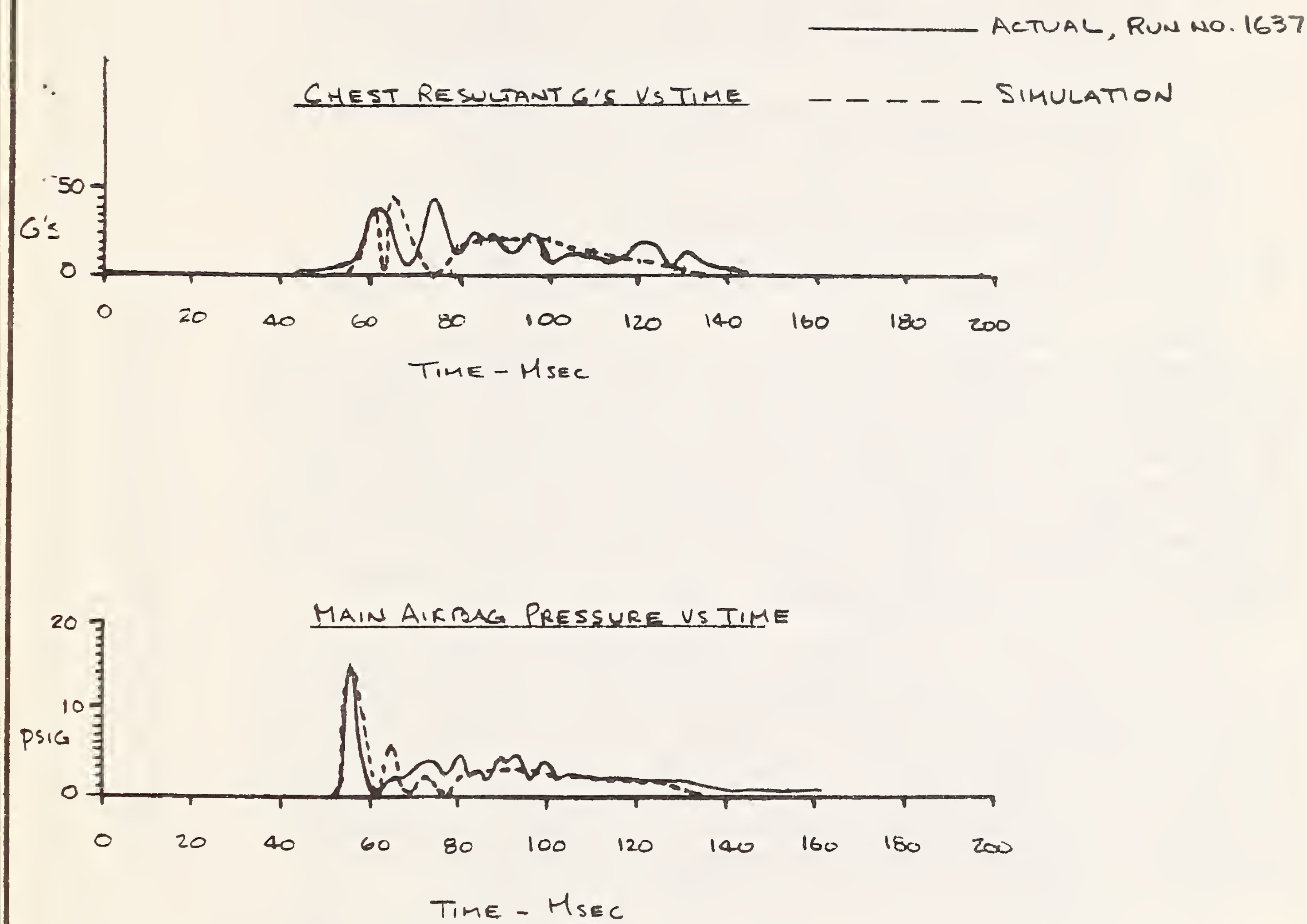
Figure 3B shows the comparison between actual test data and the computer prediction for Sled Run 1637. As can be seen in this figure, the correlation is very good, especially considering the relative simplicity of the airbag and passenger models used in the program. We believe this further validation of the program should lend sufficient credence to the DEPLOY model so that it can be used with a good degree of confidence in other out-of-position work.

Appendix B contains a copy of the actual run for this validation.

4.0 RESULTS OF SENSITIVITY ANALYSES

As previously mentioned, it was necessary to restrict this study to values of each parameter (in each of the areas of investigation listed in Section 2.0) to values that were reasonable from a design point of view. For example, it does no good to discover that a tiny airbag with a very small amount of gas results in injury measures for the forward positioned child that are quite low, if the design is such that it will not protect the adult passenger in the more normal impact situations.

Therefore the study has been restricted to parameters that make sense from a total design point of view. In order to accomplish this in a reasonable period of time, much reliance was made on past experience with both normally seated and out-of-position front seat passengers.



Test Results vs Computer Results

Figure 3B.

The approach taken in conducting this study was as follows:

1. Put appropriate bounds on the pertinent parameters for each concept studied (Gas Flow Tailoring, etc.) by using past experience and available data.

2. Run DEPLOY varying each of these parameters within these bounds.

3. Make qualitative assessments on what effect each of these parameters had on the performance of the forward positioned child and the normally seated adult for each concept.

4. Using the information gained in the above, a detailed list of the most promising design solutions was generated.

5. Generate curves and graphs that showed the effect and the inter-relationships of the parameters.

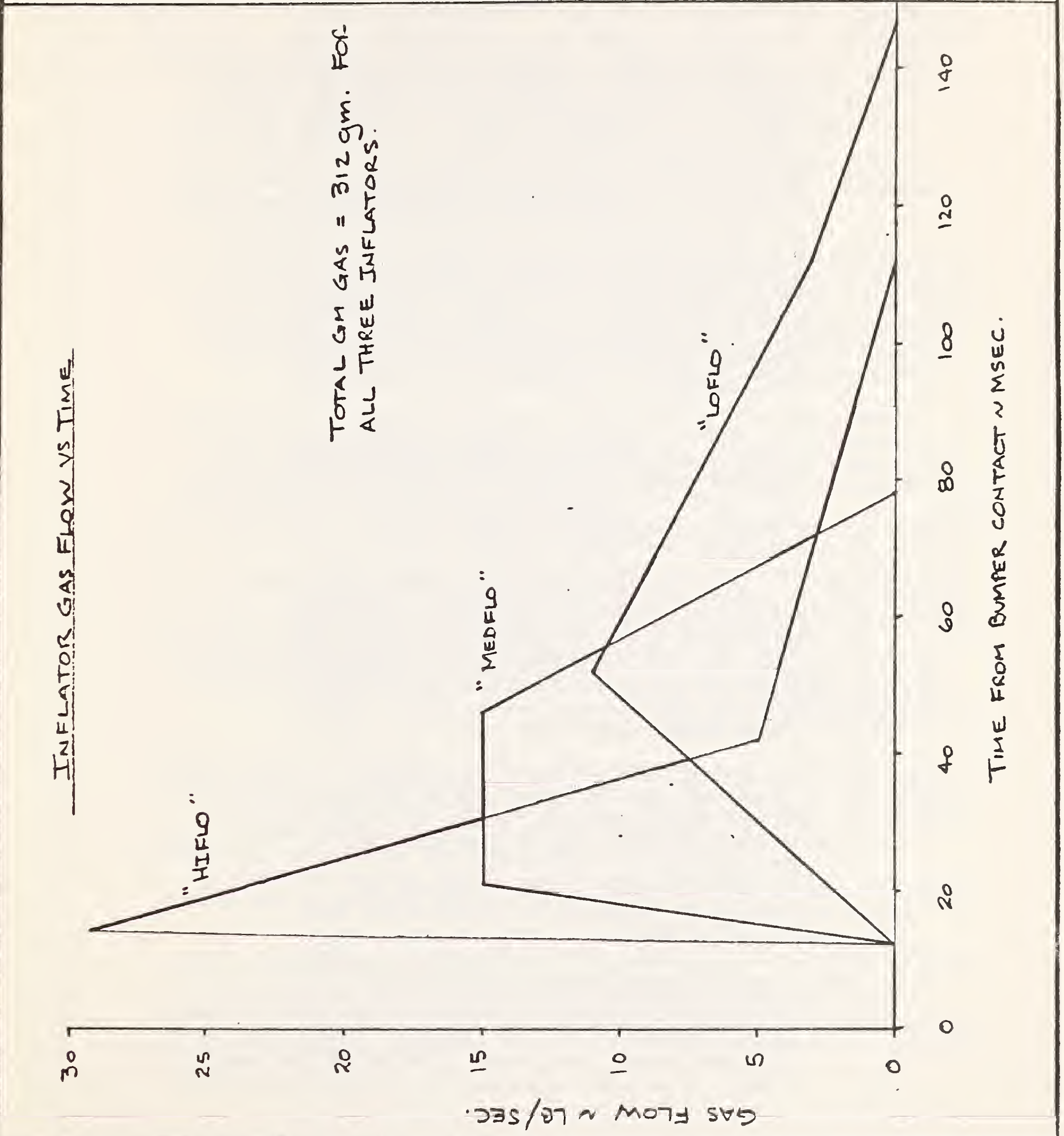
6. Investigate the next concept, i.e. repeat steps 1 through 5.

Before the results of the various analyses conducted in this study are discussed, it would be a good idea to define two terms which will be used repeatedly throughout the discussion. These terms are "bagslap" and "catapult". "Bagslap", the way it is used in this report, is defined as that portion of the total impact event from the time when the bag first impacts the chest, through full chest deflection caused by this impact, continuing until the combination of receding bag front from the chest and zero chest deflection occurs. The time in which the child is in contact with the bag after this time (unless he is in contact with the dash) is referred to as the "catapult" phase.

Therefore, repeated bag impacts due to repeated surging of the bag into the chest while the original chest deflection is positive and while the child continues to approach the deploying bag front, are considered part of the same "bagslap" event. Normally, this phase lasts longest for sustained flows where the rate of flow of gas entering the bag continues to increase with time (LOWFLO in Figure 4). With impulsive flows with high initial flow rates where the flow profile resembles a stored gas flow profile (HIFLO in Figure 4), the period of "bagslap" is usually shorter but exhibits higher bagslap g-levels on the chest.

Once the bagslap portion of the event is over (the chest deflection due to bagslap has returned to zero), the sternal mass and the main body mass are constrained to respond as a single, rigid unit for the remaining catapult phase.

With the foregoing as background, the results obtained from the study to date will be discussed.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"HIFLO"
"MEDFLO"
"LOFLO"
TIME FROM BUMPER CONTACT ~ MSEC.
0
20
40
60
80
100
120
140
GAS FLOW ~ LB/SEC.
0
5
10
15
20
25
30

Figure 4.

4.1 Effect of Fabric Weight

4.1.1 Bounding the Problem - Fabric Weight

Putting bounds on the airbag fabric weights to be used in this study was relatively easy since either coated or uncoated Nylon is used almost exclusively for production airbags by the automobile industry so that the fabric weights for the candidate fabrics is generally well known. For the few other fabrics that might be considered, the weights (oz./sq.yd.) are generally close to Nylon and also well known. Therefore one may easily select a band width of fabric weights that are representative by choosing the lightest based upon the approximate rip strength of conventional airbag fabrics at normal airbag pressures. In our experience, any fabric weight below approximately 5 oz./sq.yd. is marginal in terms of possible bag or seam tearing for normal airbag pressures, especially in the small car crash environment where the airbag must be inflated quickly to relatively high pressures.

On the other side, in our experience very few cases have ever arisen in which fabric weights greater than approximately 12 oz./sq.yd. were required. Usually even this weight was not really required but was used simply because it was readily available and one could be sure the bag had an ample safety factor.

Thus, the upper and lower bounds for the fabric weight analysis are chosen to be 12 and 5 oz./sq.yd., respectively. The only exception to this range would be if there was a strong reason to investigate further, such as to see more of a total trend in a graphical presentation.

4.1.2 Fabric Weight Effects

In discussing what was learned from the fabric weight analysis on the response of the forward positioned child, we must preview some of the results of the gas flow tailoring analysis that will be presented in detail in the following section. The reason for this is that the degree to which the airbag fabric weight affects the chest g's imparted to the child is a strong function of the inflator gas flow profile.

Figure 4 shows the three widely different gas flow profiles which were used in this study. The very fast rising curve, typical of a stored gas inflator or "ganged" driver inflators, is called "HIFLO". A more typical gas flow profile which qualitatively resembles the flow profile on most of the solid propellant gas generators used in

previous NHTSA programs is shown by "MEDFLO". A flow profile typical of what some segments of the industry are using in an attempt to reduce the chest g's on the forward positioned occupant, is shown by "LOFLO". Most known flow profiles which have been past or are present candidates for airbag usage for airbags in the ten cubic foot range fall somewhere in this regime. Further,these flow profiles encompass, in a qualitative manner, all flow profiles with which we are familiar irrespective of airbag volume.

The effect airbag fabric weight has on the forward positioned child response was investigated for the three flow profiles just described.

Three fabric weights were chosen for this portion of the study. All three fall within the bounds established in Section 4.1. The fabric weights chosen were 5.0, 8.4, and 12.2 ounces per square yard of material. A single extra case with 3.5 oz./sq.yd. fabric was tried with the LOFLO profile in order to check the curve shape for this case.

The 8.4 oz./sq.yd. Nylon fabric is a fabric which Fitzpatrick Engineering has used in numerous research programs for NHTSA and others in past years and was chosen as the middle of the range of fabric weights evaluated.

Figure 5 shows the significant results of this portion of the study. The peak chest g's in the figure are plotted versus the airbag fabric weight for the three gas flow profiles. As can be seen from the figure, for LOFLO there is virtually no effect on the child's chest response during bagslap for variations in airbag fabric weight. We therefore conclude that for "slow" gas generators one may expect fairly low chest g's during the bagslap phase and, further, these g-levels do not vary appreciably with fabric weight within the range of reasonable fabric weights.

Conversely, if the gas flow profile has a more rapid onset such as the MEDFLO or the HIFLO profiles, the fabric weight does have an effect on bagslap g's with an increase in fabric weight producing an increase in chest g's.

We therefore have two inter-related effects that occur when fabric weight is increased. The chest g's during bagslap increase with an increase in fabric mass (for MEDFLO and HIFLO) and/or an increase in the initial rate of gas flow into the bag (more about this in the next section). For very slow initial gas flow into the bag, chest g's are low during bagslap and largely independent of fabric weight.

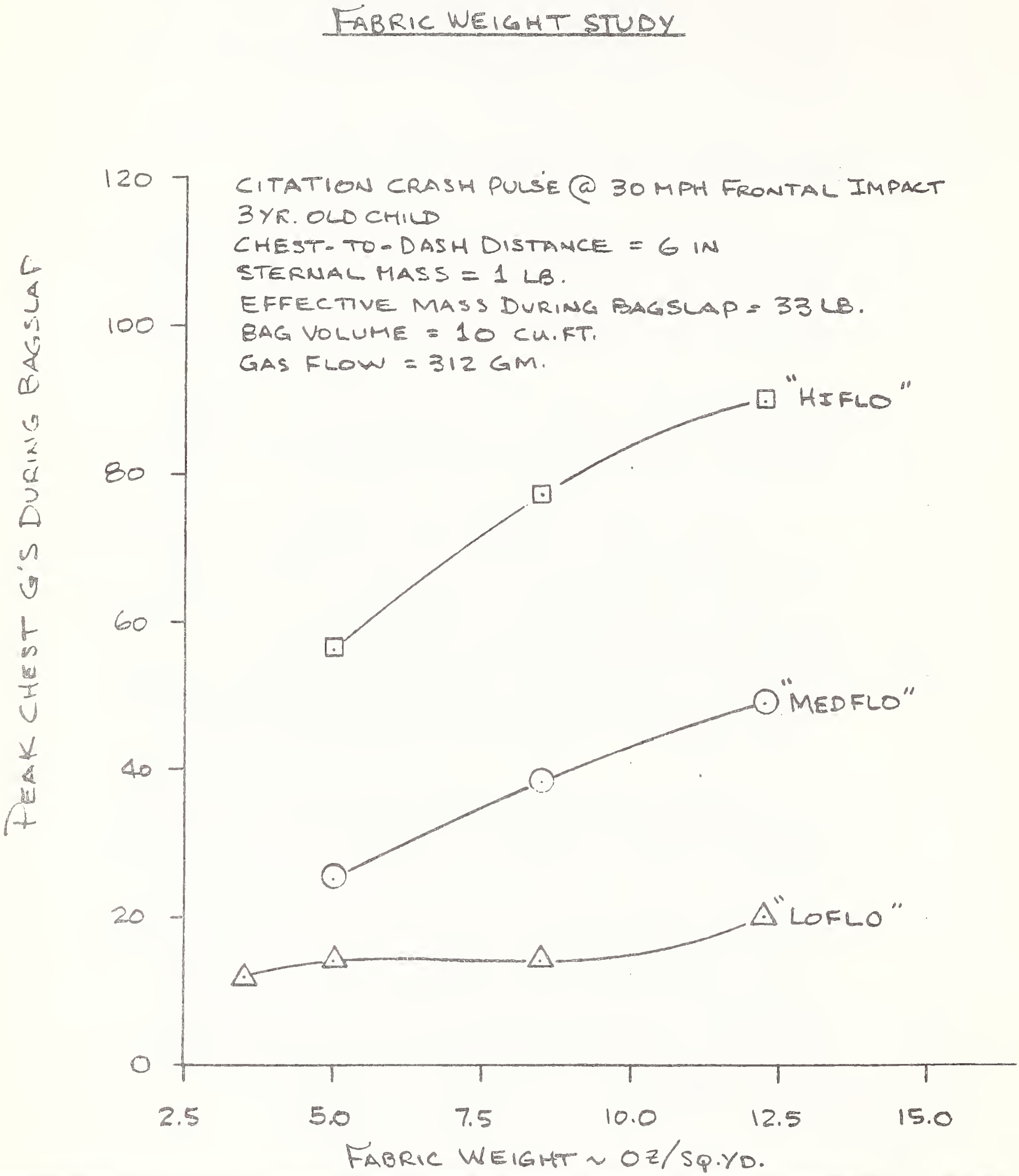

FABRIC WEIGHT STUDY
CITATION CRASH PULSE @ 30 MPH FRONTAL IMPACT
3 YR. OLD CHILD
CHEST-TO-DASH DISTANCE = 6 IN
STERNAL MASS = 1 LB.
EFFECTIVE MASS DURING BAGSLAP = 33 LB.
BAG VOLUME = 10 CU. FT.
GAS FLOW = 312 GM.
"HIFLO"
"MEDFLO"
"LOFLO"
PEAK CHEST G'S DURING BAGSLAP
120
100
80
60
40
20
0
2.5
5.0
7.5
10.0
12.5
15.0
FABRIC WEIGHT ~ OZ/SQ.YD.

Figure 5.

Please note that in the foregoing we have been discussing peak g's. If we were to plot 3 msec clipped values, the g levels would be much lower and the effect of fabric mass, therefore, less pronounced.

Figure 6 is presented to show these effects in a slightly different way. In this figure, the gas flow curves in Figure 4 have been integrated up to the time at which the peak bagslap g's are reached and then divided by that time interval. This operation yields the average flow rate in pounds of gas per second that occurred up until the peak bagslap g's were reached for each case. When these values are plotted versus the peak chest g's, we see the high dependence that bagslap g's have on rate of gas flow into the airbag.

One might ask, why do the peak bagslap g's tend to increase with increasing bag mass for the HIFLO and MEDFLO gas flow profiles? After studying the results from the computer runs it can be seen that for a given gas flow profile as bag mass is increased, it takes a little longer, perhaps one or two milliseconds, for the bag to impact the chest. This is due to the slightly lower bag front acceleration that results from the slightly greater inertia of the heavier fabric. Since more time elapses until chest contact for the heavier bag materials, slightly more gas has gone into the airbag by the time the chest is slapped by the airbag. This greater amount of flow that occurs before bagslap for the heavier fabrics means that there is a greater total amount of flow energy imparted to the bag at the time the bag slaps the chest. This greater flow energy is translated into relatively higher g's applied to the chest. This effect, as one might expect, can be related to the total average flow that has occurred up until the time of bagslap. This relationship then, is the one which has been graphically depicted in Figure 6.

For very slow initial rates of flow as in LOFLO with a relatively low average flow rate at the time bagslap occurs, there are low bagslap g's with very little difference between the different fabric masses. This follows from the description above - there is a correspondingly lower flow energy increase for LOFLO at bagslap for a given increase in fabric weight than for either MEDFLO or HIFLO.

It is not possible to make a singular statement on whether the airbag fabric weight influences the peak chest g's during bagslap. For very low rates of flow onset, the chest g's are low and do not seem to vary with fabric

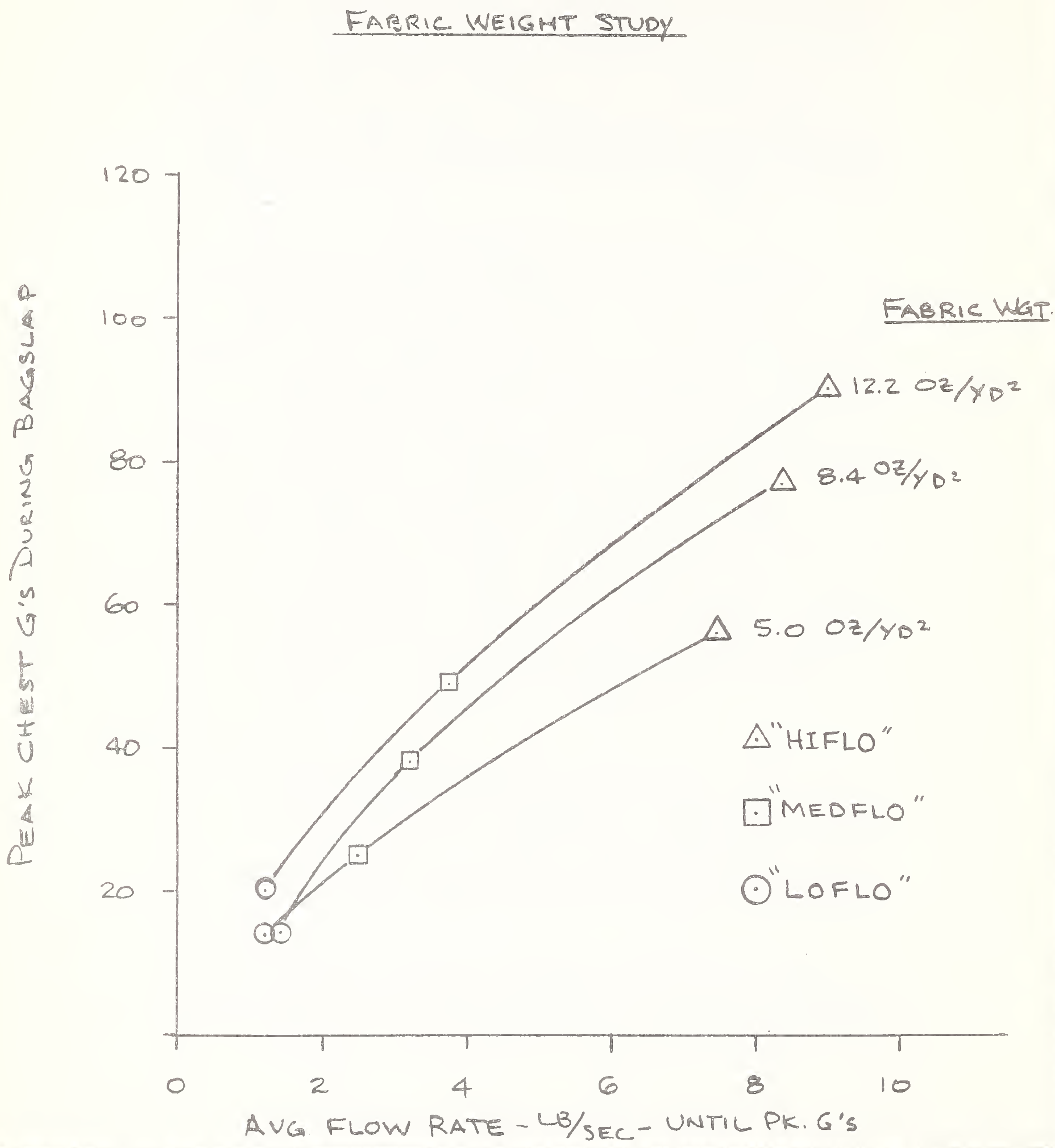

FABRIC WEIGHT STUDY
120
100
80
60
40
20
0
2
4
6
8
10
PEAK CHEST G's DURING BAGSLAP
AVG. FLOW RATE - LB/SEC - UNTIL PK. G's
FABRIC WGT.
12.2 OZ/YD²
8.4 OZ/YD²
5.0 OZ/YD²
"HIFLO"
"MEDFLO"
"LOFLO"

Figure 6.

weight. However, for high rates of initial flow, the peak chest g's are high and there is an increase in bagslap g's with increasing fabric weight.

A further conclusion which may be drawn from the results of these computer runs is that only the bagslap peak g's are influenced by fabric weight. The catapult g-levels are unaffected by fabric weight variations since the airbag is almost completely deployed with a very low amount of concentrated airbag mass remaining with which to cause significant impact forces to be generated at this late point in the crash event.

4.2 Effect of Gas Flow Tailoring

4.2.1 Bounding the Problem - Flow Tailoring

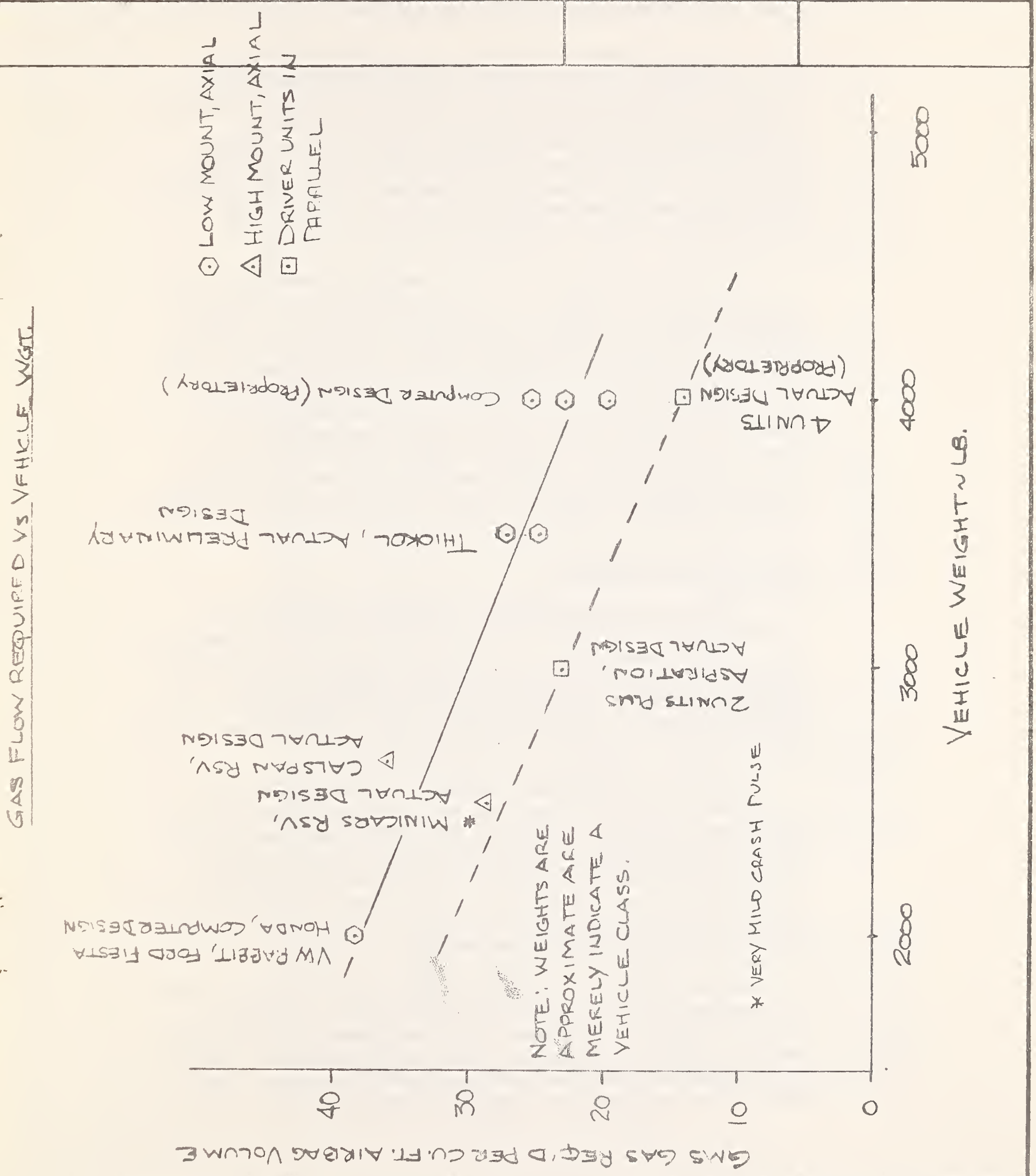
In establishing the bounds or the range of the gas flow profiles that were investigated in this computer study, it was of primary concern that the total amount of gas generated be sufficient to protect full size, normally seated passengers as well as the forward positioned child. The attempt to quantify this variable led to the construction of Figure 7.

This graph, which shows the required gas per cubic foot of airbag volume, is based upon both test results and computer results for systems Fitzpatrick Engineering has developed over the years. As such, the curves are useful in establishing a general relationship for the required total gas flow and bag volume as a function of vehicle size. Although such a curve cannot hope to cover all possible design situations, it does provide one with general knowledge on the approximate total gas flow which must be provided to satisfy the normally seated adult injury criteria. Once the approximate total required gas flow is known, we may then vary the flow profile used in obtaining this total flow in order to quantify the effect flow profile or gas flow tailoring will have on the response of the forward positioned child.

Generally speaking, the smaller the vehicle the greater the amount of gas required for a given airbag volume. This is as one would expect due to the more severe crash environment to which the smaller car and its occupants are subjected. The curve is not meant to be construed as a hard rule for airbag design, but is presented merely to show an interesting trend and to aid in obtaining valid gas flow inputs for DEPLOY.

Since the total gas flows shown by this figure are known to protect normally seated adult passengers at speeds equal to or greater than 30 mph in most crash environments, there will be confidence that if one does not stray too far from these basic relationships the restraint performance for the normally positioned passenger will not be jeopardized.

There is still a further piece of information that may be gained from Figure 7. As can be seen by examining the lower curve on the figure, the "ganged" driver generator approach to filling the passenger airbag seems to require less total gas flow for a given airbag volume. The reason for this is that this type of inflator is inherently "quicker" than a single, axial flow type of inflator resulting in low bag fill times and, therefore, a



GAS FLOW REQUIRED VS VEHICLE WGT.
LOW MOUNT, AXIAL
HIGH MOUNT, AXIAL
DRIVER UNITS IN PARALLEL
COMPUTER DESIGN (PROPRIETORY)
4 UNITS
ACTUAL DESIGN
(PROPRIETORY)
THIOKOL, ACTUAL PRELIMINARY DESIGN
2 UNITS PLUS ASPIRATION, ACTUAL DESIGN
CALSPAN RSV, ACTUAL DESIGN
* MINICARS RSV, ACTUAL DESIGN
VW RABBIT, FORD FIESTA
HONDA, COMPUTER DESIGN
NOTE: WEIGHTS ARE APPROXIMATE ARE MERELY INDICATE A VEHICLE CLASS.
* VERY MILD CRASH PULSE
VEHICLE WEIGHT ~ LB.
2000
3000
4000
5000
GMS GAS REQ'D PER CU. FT. AIRBAG VOLUME
0
10
20
30
40

Figure 7.

correspondingly greater proportion of the passsenger's kinetic energy being absorbed in the more efficient "ride down" mode rather than by bag penetration.

For this reason, if one is simulating the ganged driver generators or the similar performing stored gas, bottle "blowdown" type of gas flow profile, less total gas is required and the computer input may be modified accordingly and results compared directly to the other "slower" flow profiles where more gas is used. Figure 7 then, will serve as the general guideline in this analysis as regards the total amount of gas flow required for a given airbag/inflator design.

Looking at Figure 7 for the vehicle selected for this study, it can be seen that the Citation, which weighs approximately 2700 lbs., will require an inflator capable of delivering approximately 32 grams of gas per cubic foot of airbag volume if the inflator is a conventional, axial flow gas generator. If a quicker type of generator is used, such as those previously described, approximately 26 grams of gas per cubic foot of airbag volume will be required. This says that the range of generators which should be considered in this study should stay within the general bounds of 26 to 32 grams of delivered gas per cubic foot of airbag volume.

4.2.2 Flow Tailoring Results

Since it was impossible to discuss the effect of airbag fabric weight on chest response without discussing the inter-related effect of flow tailoring, some of the effects of flow tailoring have already been covered in the previous section. However, the effect of this very important factor on the responses on the forward positioned child will be discussed in greater detail.

Of all the parameters that were investigated as a result of the study, flow tailoring of the instantaneous mass flow rates from inflators shows the most promise for reducing bagslap g's. Unfortunately, as will be pointed out in the following discussion, somewhat of a dilemma exists since the flow profiles that reduce bagslap g's tend to increase the catapult g's of the child as well as the chest g's of normally seated adults.

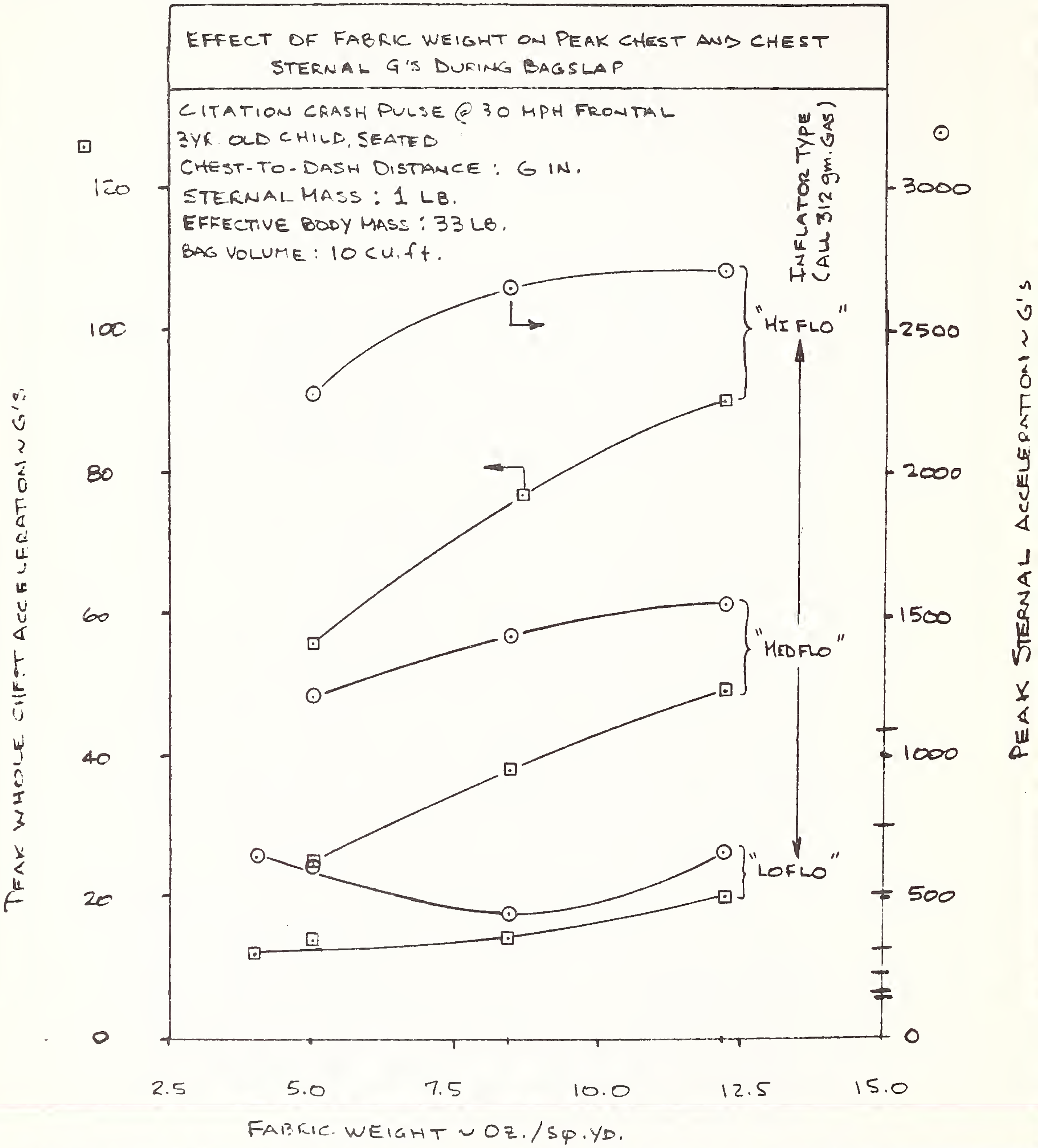
Before going on to discuss the details of this study, one comment will be made here. The results presented reflect computer input data that represents as "closely as possible" that of an actual three year old child. However, "as closely as possible" may be somewhat different from what it actually may be. NHTSA has assisted Fitzpatrick

Engineering in searching for valid data on the child chest properties such as dynamic force-deflection properties and damping coefficients for use as computer input data. Unfortunately, very little (almost nothing) exists in the literature on what these properties might be. Therefore the input data used in the program was a mixture of scaled down adult data and measured three year old dummy data. Even the ratio of sternal mass to whole body mass was difficult to establish. Since good correlation with adults as found in computer simulations for a mass ratio of 1:40, and since the ratio was thought to be slightly higher for the child, a sternal mass to whole body mass ratio of 1:33 was used in our simulations, i.e. a 1 lb. sternal mass for the 33 lb. child.

Limited data was available on the values of chest surface accelerations indicated when accelerometers were mounted just under the chest surface in recent forward positioned child sled tests and these data points are shown on the right ordinate in Figure 8 and compare in a qualitative sense with the peak sternal g's predicted by the DEPLOY computer program. "Qualitatively" is used because the crash environment was different in the tests than simulated with the program. These results, however, provide the only data with which we are familiar in which accelerometers were placed on the child dummy in a manner that would permit us to estimate sternal g's and, therefore, provides our sole piece of data from which we may infer whether or not the program predicts even qualitatively, what the peak sternal g's may be.

However, from the figure we see that the values predicted by the computer correspond in magnitude to those actually seen in the tests when the LOFLO flow profile is the gas flow source. The fact that it is the LOFLO profile that matches actual test data most closely is interesting since it is the LOFLO type of flow profile that is most likely the one actually used in these tests. In fact, the LOFLO profile was provided by inflator manufacturers as an example of the types of flow profile generally being used by the industry to meet the child injury criteria.

Let us now discuss Figure 8 in more detail. The right ordinate, as discussed above, represents the absolute peak sternal acceleration during the bagslap phase which is the time the g-levels are highest. The values are much higher than the whole body g-levels since the stermal mass is only one pound; however, one must keep in mind that these high g values only last for a very short time. In fact, the whole duration of a cycle in which the stermal g's climb from zero to the maximum and back to zero again is almost always less than two or three milliseconds.



EFFECT OF FABRIC WEIGHT ON PEAK CHEST AND CHEST STERNAL G'S DURING BAGSLAP
CITATION CRASH PULSE @ 30 MPH FRONTAL
3YR. OLD CHILD, SEATED
CHEST-TO-DASH DISTANCE : 6 IN.
STERNAL MASS : 1 LB.
EFFECTIVE BODY MASS : 33 LB.
BAG VOLUME : 10 CU.FT.
INFLATOR TYPE (ALL 312 gm. GAS)
"HI FLO"
"MED FLO"
"LO FLO"
PEAK WHOLE CHEST ACCELERATION ~ G'S
PEAK STERNAL ACCELERATION ~ G'S
FABRIC WEIGHT ~ OZ./SQ.YD.
0
20
40
60
80
100
120
500
1000
1500
2000
2500
3000
2.5
5.0
7.5
10.0
12.5
15.0

Figure 8.

The left side ordinate reflects the absolute peak whole chest or whole body accelerations that occur during the bagslap phase. Again, the abscissa is the airbag fabric mass with the various gas flow profiles grouped as shown in the figure.

The effect of fabric mass was discussed in the previous section and will not be repeated here. Now we will direct our attention to the various gas flow profiles.

As can be seen from this figure, both the peak sternal g's and the peak whole chest g's increase with an increase in the rate of flow onset (the slope of the curves shown in Figure 4) as we proceed from LOFLO to HIFLO. Inspecting these bagslap results alone it might be said that the best design would use a LOFLO gas flow profile.

However, let us now look at Figure 9 in which the abscissa is incremented into the LOFLO profile, the MEDFLO profile and the HIFLO profile. Here the abscissa has no specific numerical or quantitative value but is used qualitatively to show the effect the individual flow profiles have on the peak bagslap g's and the peak catapult g's for the out-of-position child and the peak chest g's for the normally seated adult. Please note that in this figure, unlike previous figures, the "peak g's" reflect 3 msec clipped values rather than absolute peak values. Also note in Figure 9, the effective body mass during the bagslap phase only, was taken to be one-half of the total body mass of 33 lbs. This factor was found during the validation effort described in Section 3.2 to yield values closest to actual test values.

In Figure 9 the previously mentioned dilemma becomes obvious. If we were to design our restraint system based only upon realizing lowest bagslap g's for the child, we would select the LOFLO type gas generator. However, this choice would result in the highest catapult g's for the child and the highest g's for the normally seated adult. The reason for this is that a slow flow onset, such as LOFLO exhibits, reduced the velocity of the bagfront at the time of bagslap with correspondingly low bagslap g's. However, this same flow profile also reduced the amount of the passenger's kinetic energy that is absorbed by "ridedown" resulting in excessively high g's for the normally seated adult and the forward positioned child during the later stages of the impact event.

If in trying to reduce the catapult g's by increasing the amount of energy absorbed by ridedown through changing to a gas generator with a flow profile more like MEDFLO or HIFLO, one could end up drastically increasing the bagslap

CALCULATION SERIAL NO

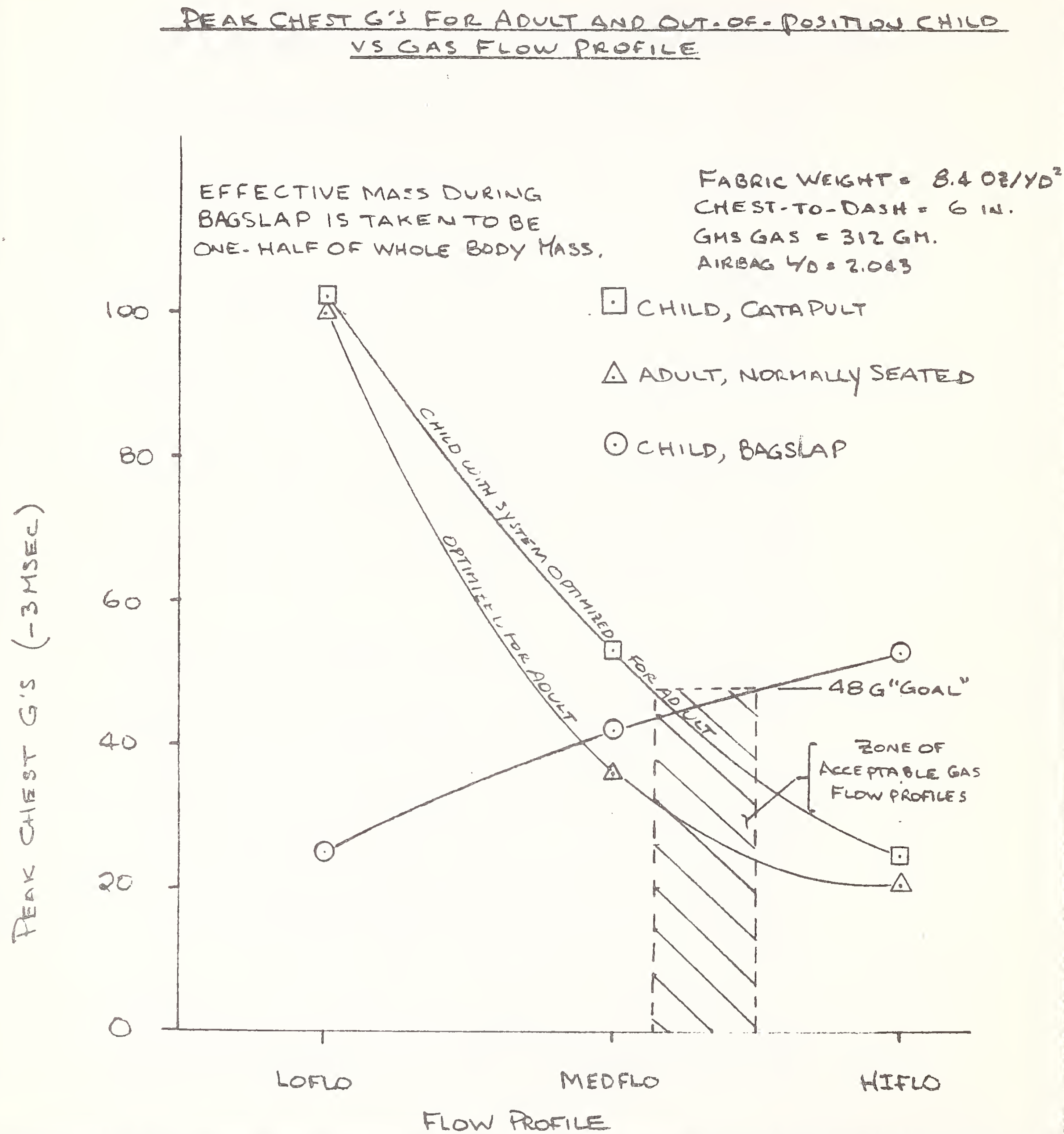


Figure 9.

g's since the velocity of the deploying airbag is significantly increased. Are there any desirable solutions to this tradeoff?

One thing which could be done is to merely look for the zone (if one exists) where the injury criteria is satisfied for both bagslap and catapult. Figure 9 shows where this zone would be for a 48 g (80% criteria limit) goal on maximum chest g's assuming 8.4 oz./sq. yd. fabric (60 g wasn't used as the criteria limit since to design to this goal would result in an unacceptably large statistical probability that it could be exceeded in compliance testing). Two other zones of "satisfactory" system designs could be constructed for the 12.2 and the 5.0 oz./sq. yd. material. The net effect would be to raise the confidence level on meeting the chest g criteria as the fabric weight is reduced, while increasing the probability the bag would fail as the favored generator begins to tilt toward the HIFLO generator with its higher initial bag pressures.

We feel there are some drawbacks to selecting the gas flow profile based merely on the tradeoff considerations of falling with the zones constructed on the figure. These reasons are discussed in the following section.

4.2.3 Possible Directions in Gas Flow Tailoring

In the previous section "zones of designs" were described as shown in Figure 9 which would theoretically meet the combined requirements of the out-of-position child and the normally seated adult. A drawback to this particular type of solution is that a "compromise" solution is called for; i.e., the type of flow profile chosen to satisfy the normally seated adult requirements would not be optimum for the child and vice-versa. If only the adult were to be considered, one would choose a flow profile that was of rapid onset such as HIFLO or MEDFLO with a relatively large amount of total gas flow would be prudent. Conversely, if one had only the child to consider, one would limit the total amount of gas flowing into the airbag to an amount less than that required for the adult.

A compromise design is somewhat unsatisfactory since the normally seated adult, who will occupy the passenger seat by far the greatest amount of the time, will receive somewhat higher injury measures as a result of the gas flow modifications made to accomodate the forward positioned child. If this happens, on a societal cost basis, we may well see a net loss in total benefit with a corresponding net increase in costs.

catapult g requirements optimally, but it became apparent that there could even be various levels of "proficiency" within the different concepts of providing the dual flow profiles.

Aspirated Systems

For example, a drawback to the aspirated and pressure dump systems is that the flow up until the time the bag would slap the forward positioned child's chest is the same for both the child and the normally seated adult. That is to say, the early part of the flow profile is fixed and will vary from what the normally seated adult flow profile would be only after chest contact with the forward positioned child has actually occurred. Therefore, the aspirated system does not attenuate the bagslap g's that would be imparted to the child very much if at all because, as we have pointed out, bagslap g's are the result of the gas flow into the bag up until bagslap actually occurs. For this reason, an aspirated inflation source can, at the limit, only lower catapult g's. Additionally, the flow profile that must be provided up until bagslap must be somewhat of a compromise since bagslap g's cannot be allowed to be excessive but, at the same time, ridedown must not be limited too much.

For the reasons described above, a relatively slow flow onset is required for the aspirated system regardless of the size of the passenger actually occupying the seat. Therefore, the aspirated inflation system is not a true dual level system in that the beginning of the flow, up until bagslap occurs, must be programmed to limit bagslap g's which will, like other single level inflation systems, compromise the normally seated adult performance by not maximizing the ridedown potential for the system.

Staged Inflation

Now consider staged inflation. In a staged inflation system, several inflators, or a single inflator with two or more flow profile stages are used in order to obtain the desired flow profile. Here again, however, a true dual level system is not present since one can vary only how many of the stages are actually programmed to fire in any given impact or

seating configuration. The only way such a system can be a truly dual level system is if the degree of staging flexibility is such that the very beginning of the flow profile would be regulated to be optimal for the size and seated configuration of the passenger occupying the seat.

Dual Level Gas Generators

A true dual level system then, has the ability to generate two entirely different flow profiles from beginning to end, and has some built in logic that tells it which of the two flow profiles to provide in a given crash condition, seated configuration, or passenger size in order to optimally meet the requirements for that condition. One such system which would provide this dual level function will now be discussed.

Consider the following system in which a dual level inflation system generates the flow profile shown by the lower curve in Figure 10 for the condition where the forward positioned child is occupying the passenger position, and the upper curve in Figure 10 when a normally seated adult occupies this position. Notice that the upper curve is the HIFLOW curve while the lower curve is a new flow profile called NEWFLO created specifically to lower the bagslap g's on the child. For the sake of comparison, included in Table 1 are the results for the single level HIFLO system along with the dual level HIFLO-NEWFLO system.

Table 1

Flow Profile	Adult G's	Child Bagslap G's*	Child Cat. G's*
HIFLO	20.5	53	25
HIFLO-NEWFLO	20.5	43	32

* Values based upon a mass factor on whole body mass of one-half during the bagslap phase. Values are 3 msec clipped values.

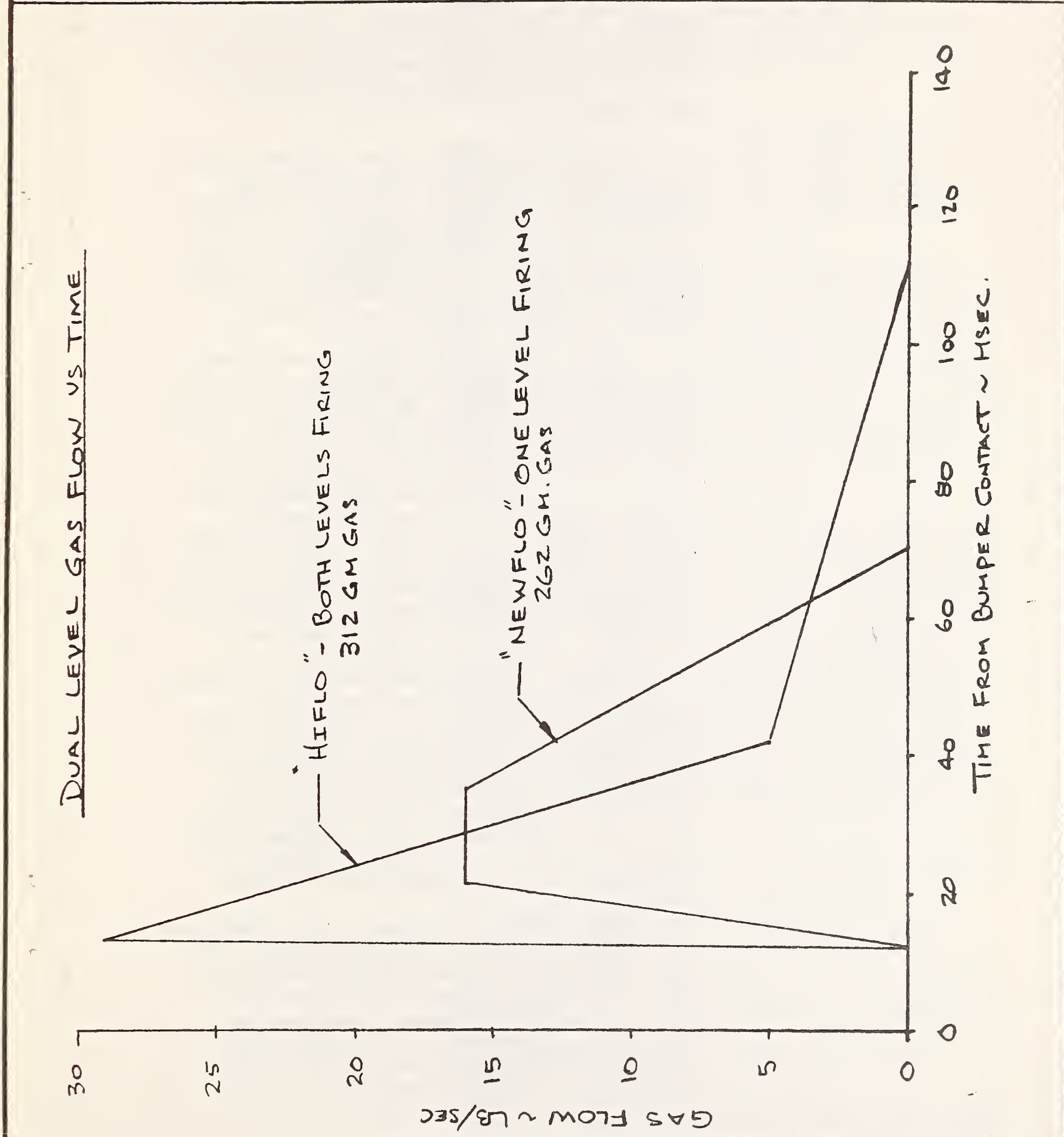

DUAL LEVEL GAS FLOW VS TIME
"HIFLO" - BOTH LEVELS FIRING
312 GM GAS
"NEWFLO" - ONE LEVEL FIRING
262 GM. GAS
GAS FLOW ~ LB/SEC
TIME FROM BUMPER CONTACT ~ MSEC.
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140

Figure 10.

By examining the results shown in Table 1 it can be seen that the bagslap g's are considerably reduced by using the dual level system. The adult g's remain the same as before since the HIFLO profile was used in both cases for the adult and was the flow profile which was most efficient for the normally seated adult (Figure 9).

The above analysis serves to show, through example, the feasibility and, indeed, the desirability of using a true dual level system to individually tailor the flow into the bag for the two conditions described above. It is anticipated that additional computer searching would undoubtedly turn up even better designs; however, the point has been established.

The desirability of having a dual level inflation source has been established, but what about the practicality? We believe the design and fabrication of a dual level inflator is not difficult, and is well within the state of the art of those in the solid propellant system business. In fact, several such systems were fabricated and tested a few years ago to provide individual flow profiles for different impact velocities. Since this time, the state of the art has improved still more so that flow profiles of almost any shape may be achieved by making the appropriate design adjustments.

The main remaining question to be answered is, "How might the dual level system be triggered so that the correct flow profile was activated for the corresponding passenger size and position?". This question will be addressed by proposing two possible design solutions. Please keep in mind, however, that it is beyond the scope of this program to be exhaustive here; and it is merely meant to be shown here that such designs are feasible.

A few years ago the auto industry designed seat belt systems for the passenger seat that would sense whether the seat was occupied or not. If there was someone in the seat and the seat belt was not fastened, a buzzer would sound and would continue until the belt was fastened. One possible way to trigger the particular flow profile desired in a given

situation would be to provide a seat sensor directly under the part of the seat where a normally seated person would reside (Figure 11). When the switch was closed, both levels would fire and the HIFLO flow profile (or one like it) would fill the bag.

For a child seated out-of-position on the edge of the seat or standing on the floor in front of the seat, no switch closure would occur and only the single level would fire so that the NEWFLOW flow profile (or one like it) would fill the bag (Figure 12).

Further analysis on the computer with the DEPLOY program and experimental testing would show whether one wanted the single level or the dual level to fire when the child was normally seated. If both levels were desired, the system described above would suffice. If, here again, only the single level was desired, one could provide a spring bias on the seat sensor switch that would only close the switch for a heavier weight person on the seat.

Another way to initiate a truly dual level system would be through a judiciously designed crash sensing scenario. The high level system would be triggered by high delta V (say 30 mph) sensors located as far forward in the car structure as possible. Should the bumper or radiator cross member undergo say a 30 mph delta V in the first few miliseconds, a high level crash would be indicated and high level deployment would be the appropriate response. Low level sensors would be located further back in the car structure to avoid inadvertent deployment should a low level delta V crash be indicated.

The above discussion is presented to show that, first, one does not necessarily have to compromise performance in order to have a restraint system that performs optimally for both the adult and the child. Secondly, two such systems that could be constructed only out of hardware previously developed are described that would meet this criteria. Knowledgable persons will be able to design even better systems once attention is directed to this area. The purpose of this study is merely to point out these computer revealed solutions and to focus attention to the appropriate areas where improvements appear possible and promising.

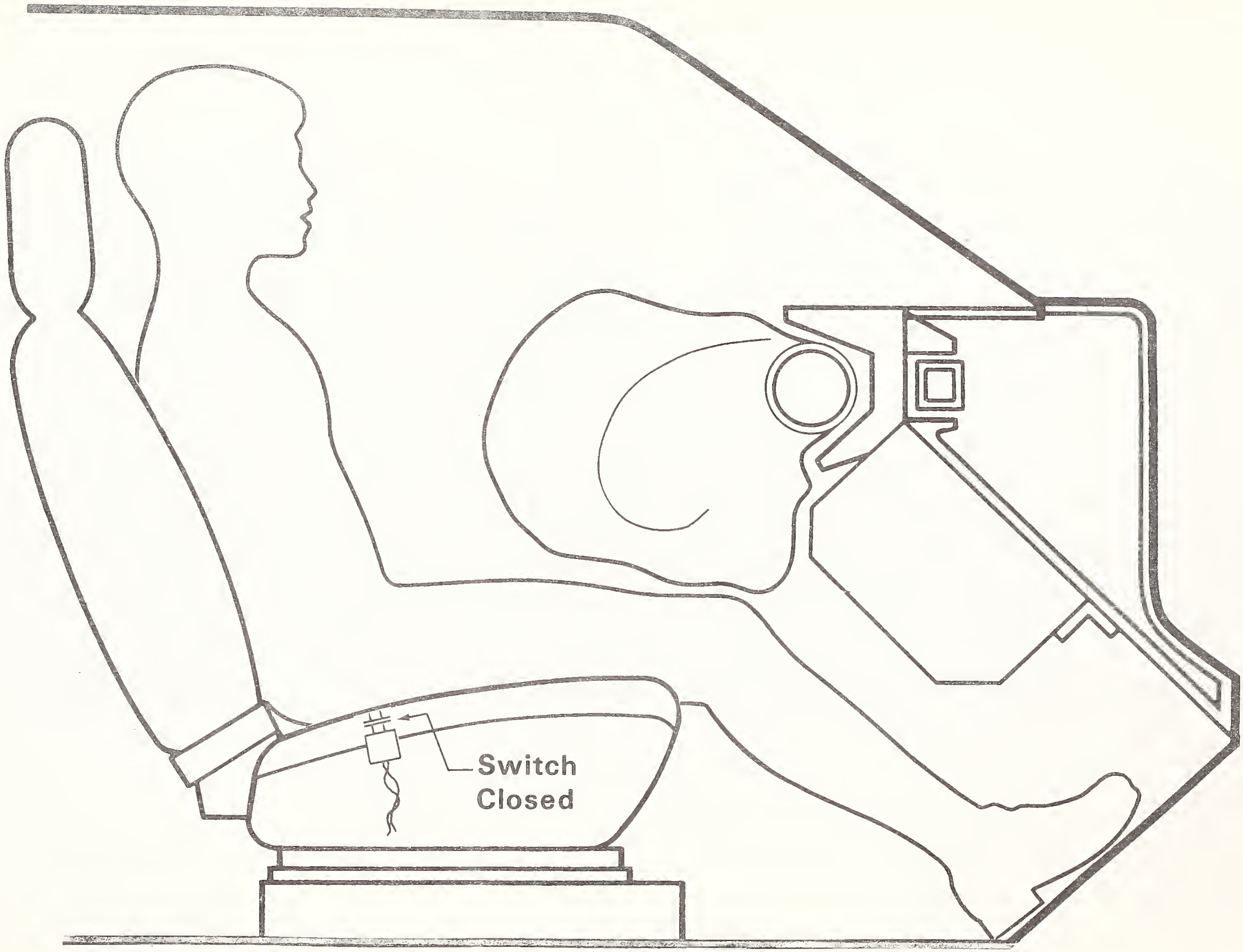


Figure 11

Normally Seated Adult

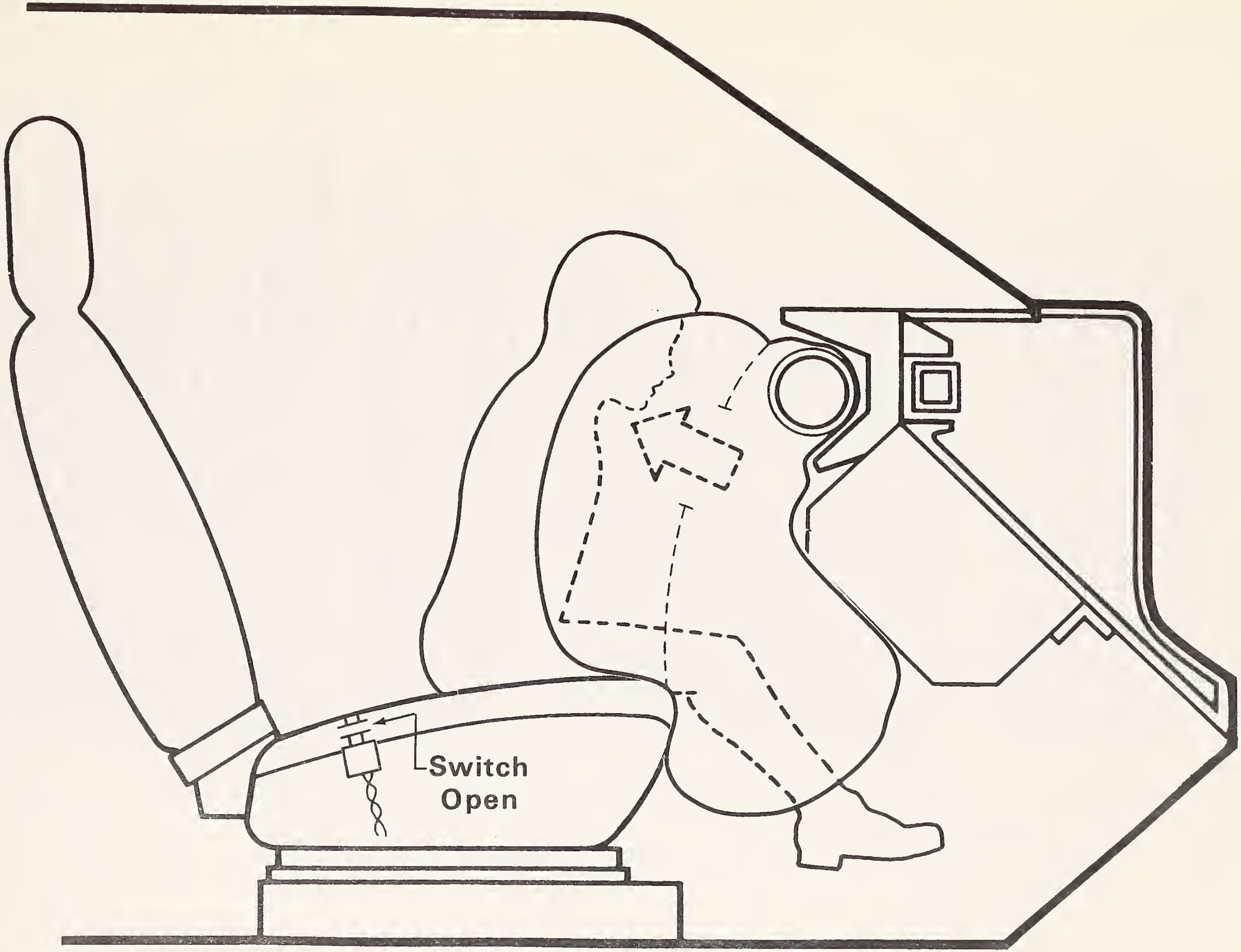


Figure 12

Out-of-Position Child

4.2.3.2 Dual Cell Airbag

In conducting the computer simulations for this study the important influence that flow tailoring has on the performance of the restraint system in protecting the forward positioned child and the normally seated adult was discovered. More specifically, the desirability of having a dual level inflator to provide a separate, optimal flow for each of these two conditions was identified.

As these results were obtained it became clear why an experimental system developed a few years ago as part of another NHTSA contract performed as it did. In this program (Development of a Solid Propellant Inflation Technique, Contract No. DOT-HS-6-01384) a solid propellant inflator that would provide the dual protection function in a similar optimal fashion was being developed. Due to the limited scope of that program Fitzpatrick Engineering was unable to do a great deal in actual flow tailoring through modification of the inflator design parameters. However, relatively good success at 45 mph impact velocity was achieved by making use of a very important concept that, unknown specifically at that time, provided, in essence, this same dual level inflation capability.

In the particular airbag design on this contract there were two individual cells. One cell, the lower cell, received gas directly from the inflator causing this cell to fill very quickly. The other cell, the upper cell, received its gas through a vent in the membrane dividing the two cells (Figure 13).

When the forward positioned child was being tested, the lower cell of the airbag came out and hit the chest and then rotated downward until it hit the floor and became wedged between the floor and the seat so that the bulk of the inflation energy was reacted by the seat. The upper cell then came into contact with the child's chest and head and provide his primary means of restraint. The upper cell filled more slowly through the membrane vent than the lower cell which was inflated directly from the inflator. In essence, a lower flow rate system was operating for the standing child (see Figures 14 through 16).

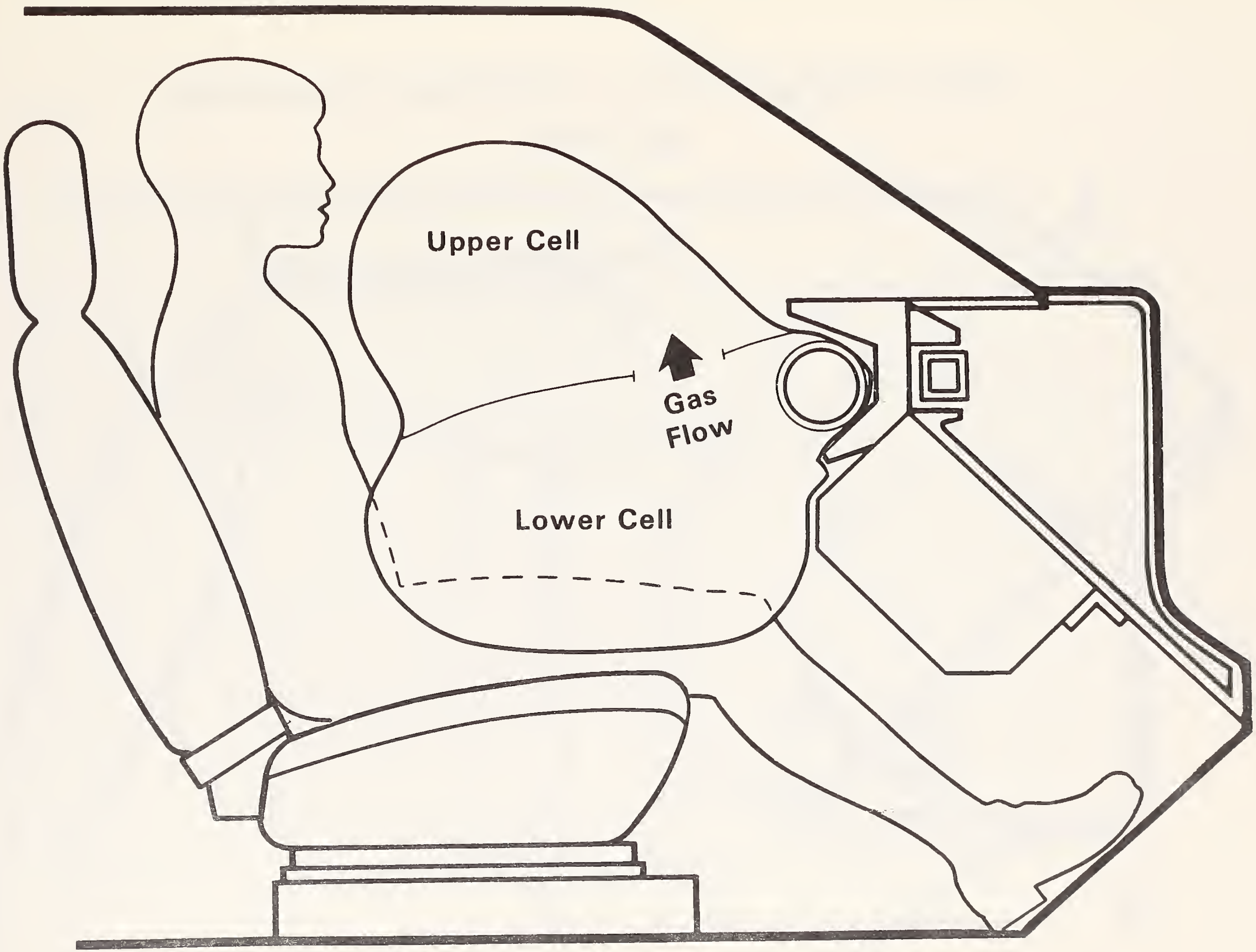


Figure 13
Dual Cell Airbag

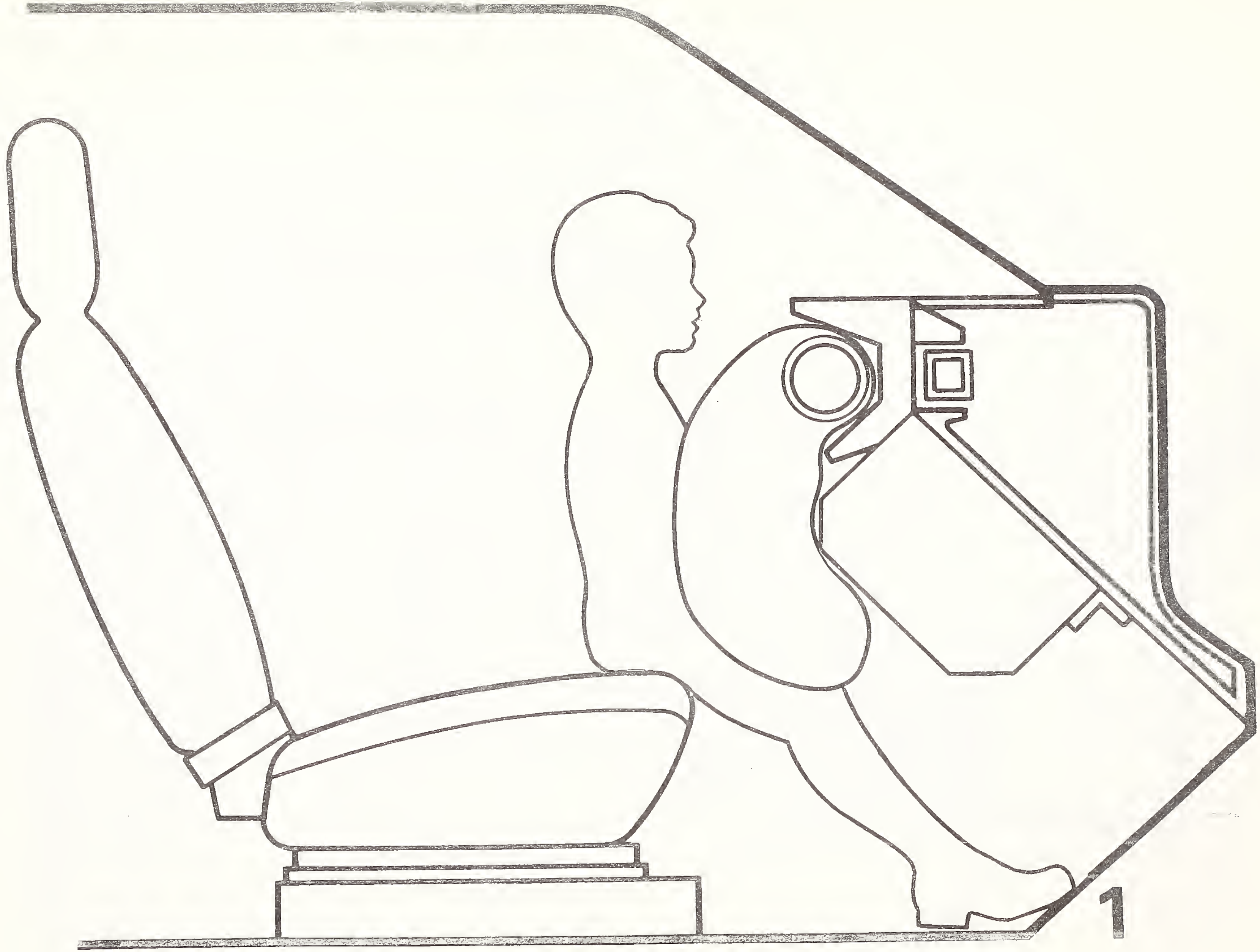


Figure 14

Deployment Sequence — Out-of-Position Child

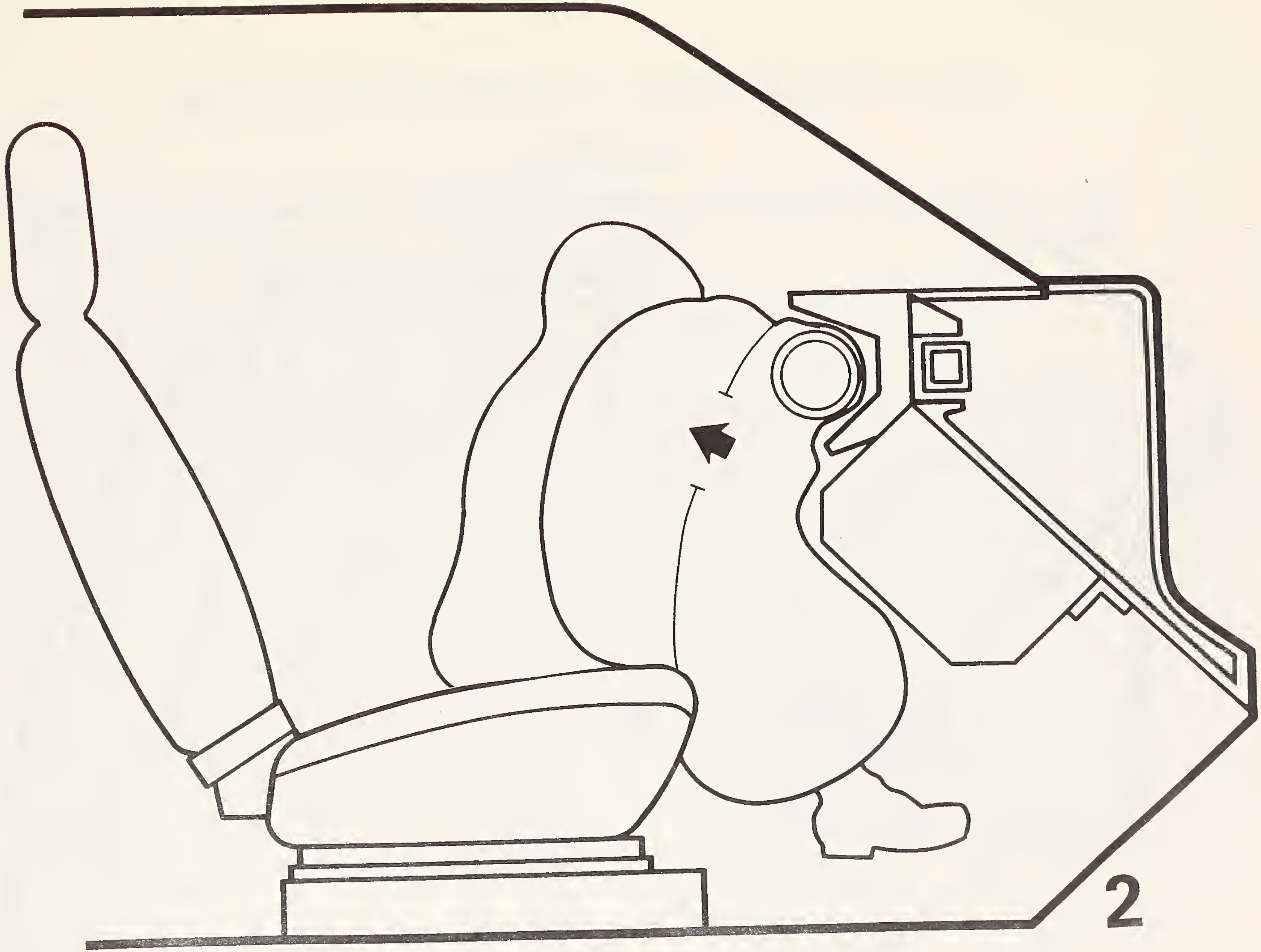


Figure 15

Deployment Sequence — Out-of-Position Child

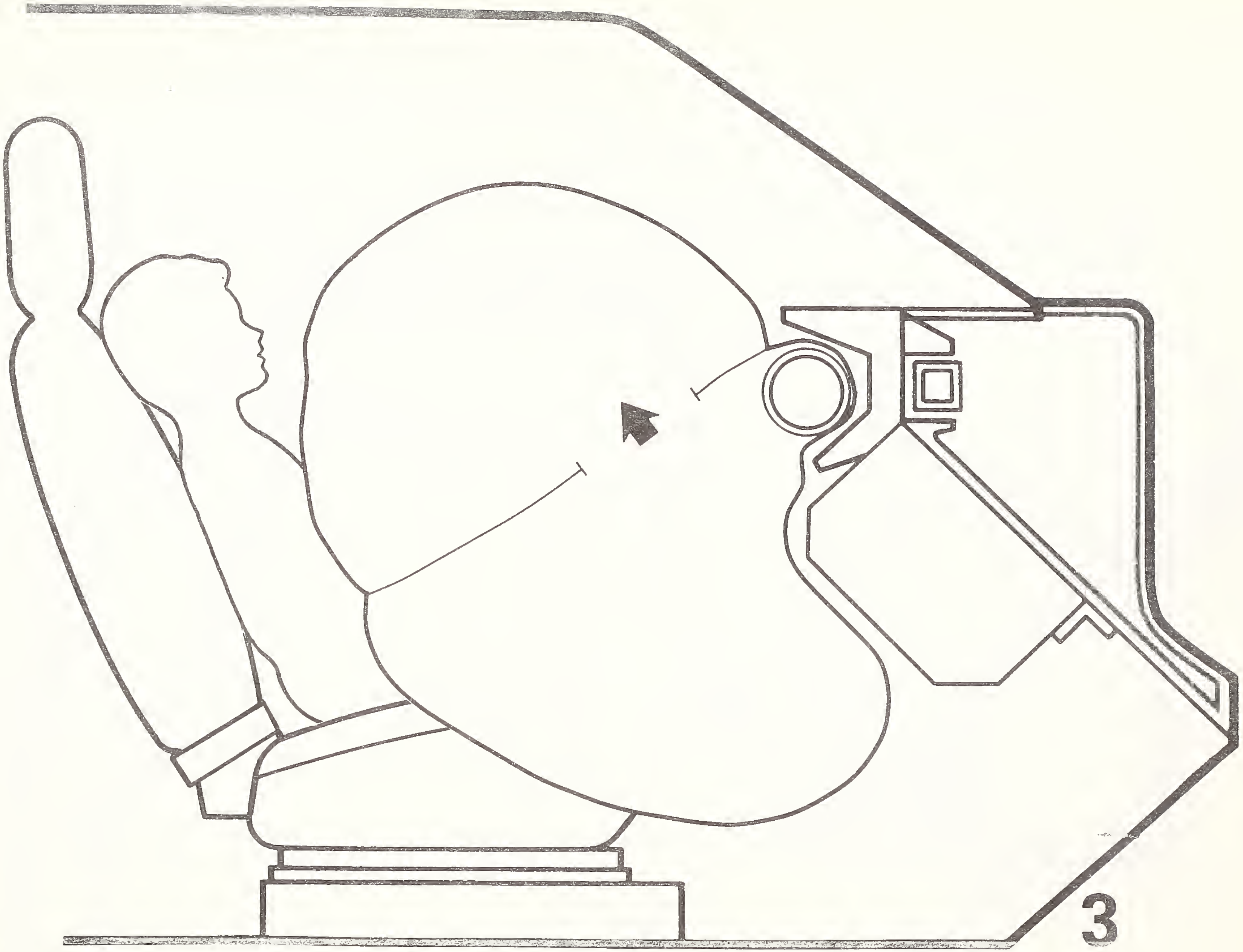


Figure 16

Deployment Sequence — Out-of-Position Child

However, when a normally seated adult occupied the passenger seat, the bag deployed normally bringing the harder, more quickly filled lower cell into rapid contact with the chest, thereby resulting in a large percentage of the passenger's kinetic energy being absorbed by the efficient ridedown mode. Therefore, in this case, the dual flow levels were provided not by tailoring the gas flow from the generator per se, but by an effective flow tailoring that resulted from the differing bag deployment geometries for the two seated configurations (see Figures 17 through 19).

The type of system described above performed marginally for the forward positioned child at 45 mph but might hold promise for 30 mph impacts where only approximately one-half the kinetic energy must be absorbed by the airbag. Although this dual level scenario would probably not be as consistent as direct inflator flow tailoring, this scenario is presented merely to show a further way in which one might provide a dual level system or enhance the effects of a dual level inflator, or both.

4.3 Effect of Airbag Shape

In this portion of the analyses, the effect of airbag shape on the response of the out-of-position child to the deploying airbag will be investigated. All parameters except the airbag length-to-diameter ratio and the gas generator flow profile have been held constant at the values used in the previous parts of the study. The values held constant were:

a) The chest-to-dash distance of six inches

b) The airbag volume of ten cubic feet

c) The total amount of gas following into the airbag of 312 grams

d) The fabric weight of 8.4 ounces per square yard

e) The Citation crash pulse

f) The three year old child anthropometric properties.

The objective, therefore, is to obtain a relationship between airbag shape and gas flow profile as they affect the degree of injury an out-of-position child might experience in a given crash situation.

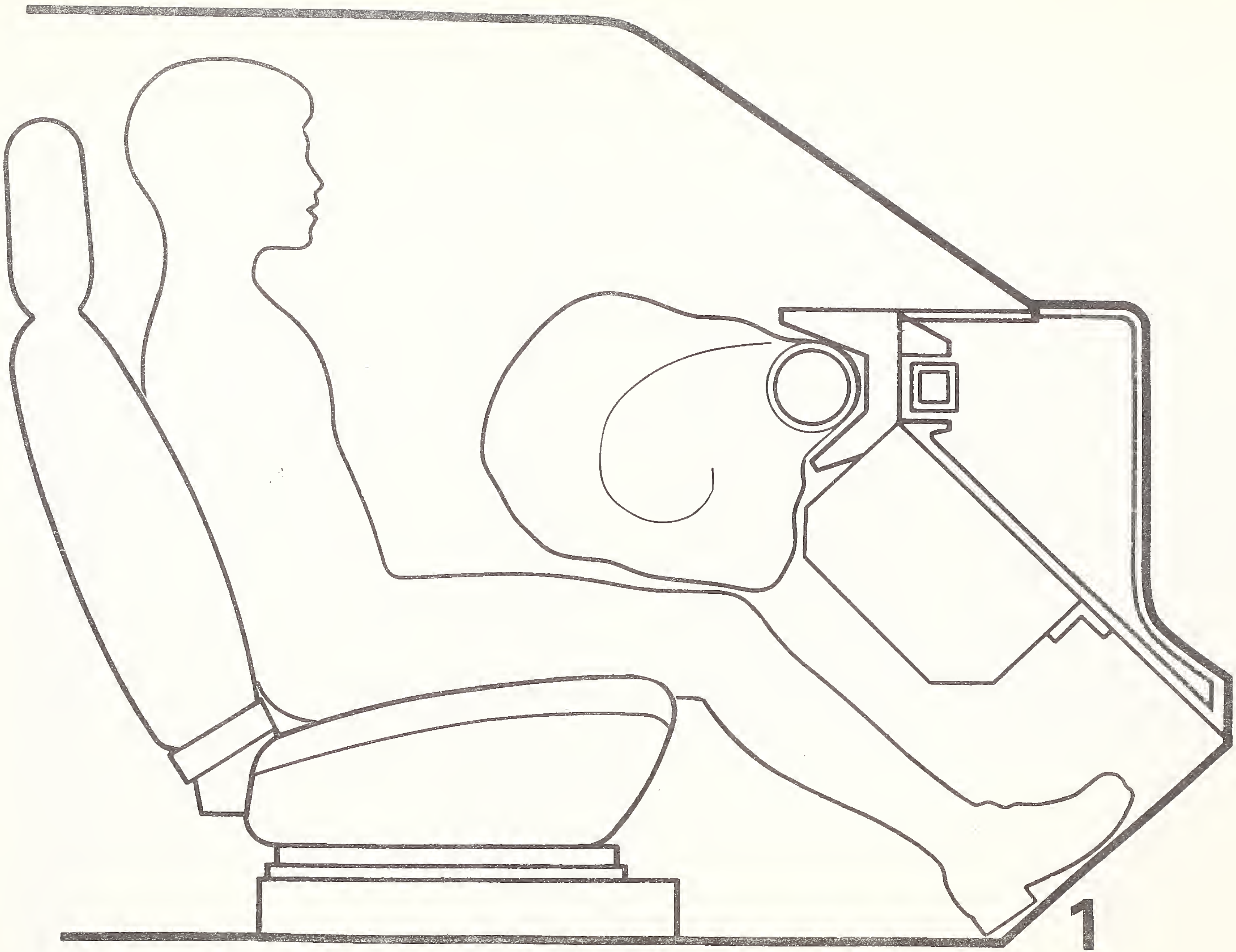


Figure 17

Deployment Sequence — Normally Seated Adult

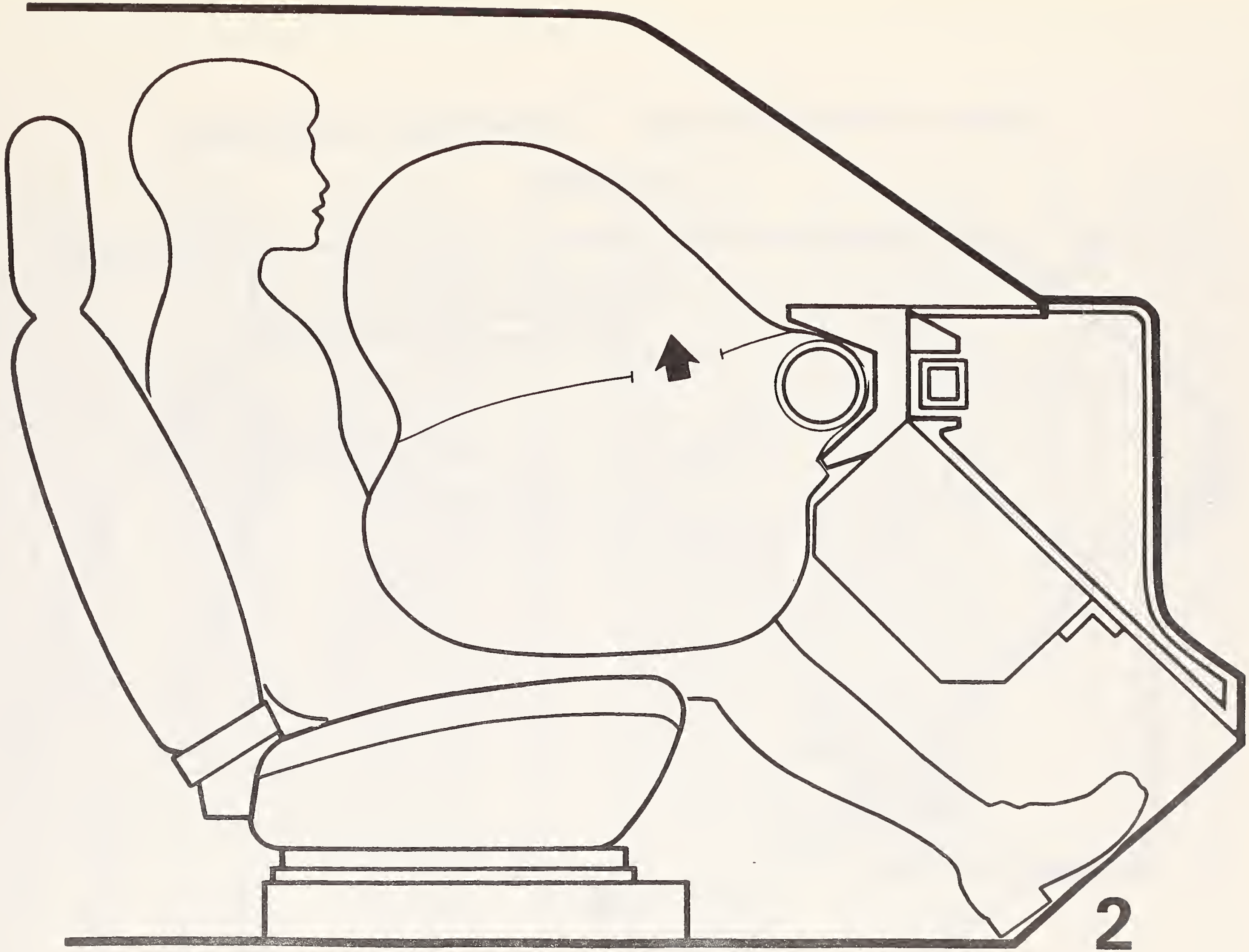


Figure 18

Deployment Sequence — Normally Seated Adult

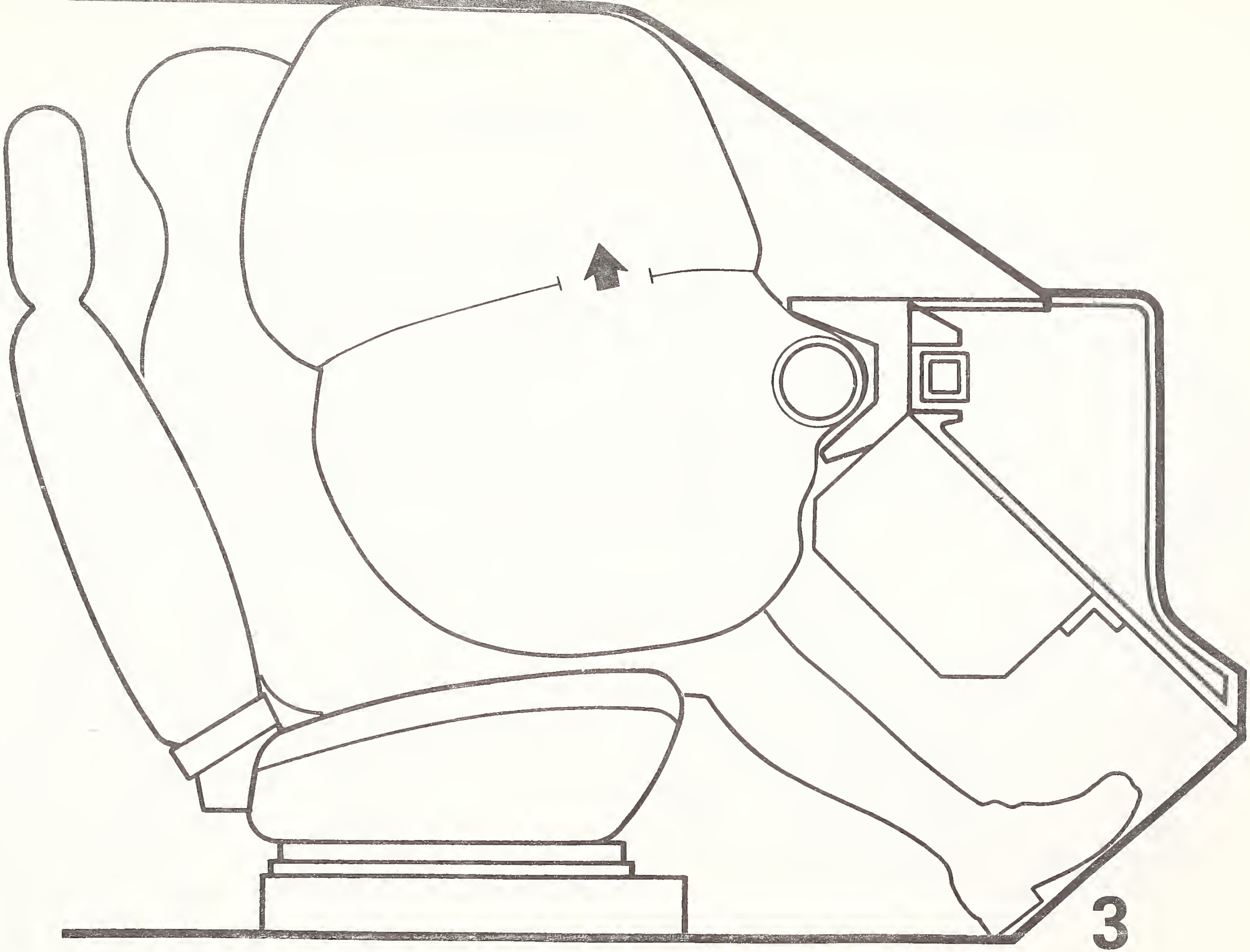


Figure 19

Deployment Sequence — Normally Seated Adult

The limits over which the airbag shape were varied are shown in Figure 20. As can be seen in the figure, the limits chosen cover the entire range of possible bag shapes (consistent with a cylindrical airbag with hemispherical ends) one might consider for a potential airbag design.

The limits over which the gas flow profiles were varied were the same as before and are shown in Figure 21. The results of the airbag shape study will now be discussed.

In Figure 22 the results for an L/D ratio of 1.0 are presented. Plotted are the peak chest g's with 3 msec clip versus the gas flow profile. Both the peak chest g's during the bagslip phase and the catapult phase have been presented to facilitate understanding the mechanisms that work together to produce injury. As before, a goal of 48 g's peak chest acceleration has been selected as acceptable. This is 80% of the 60 g criteria limit and is a reasonable design goal for the 60 g criteria limit.

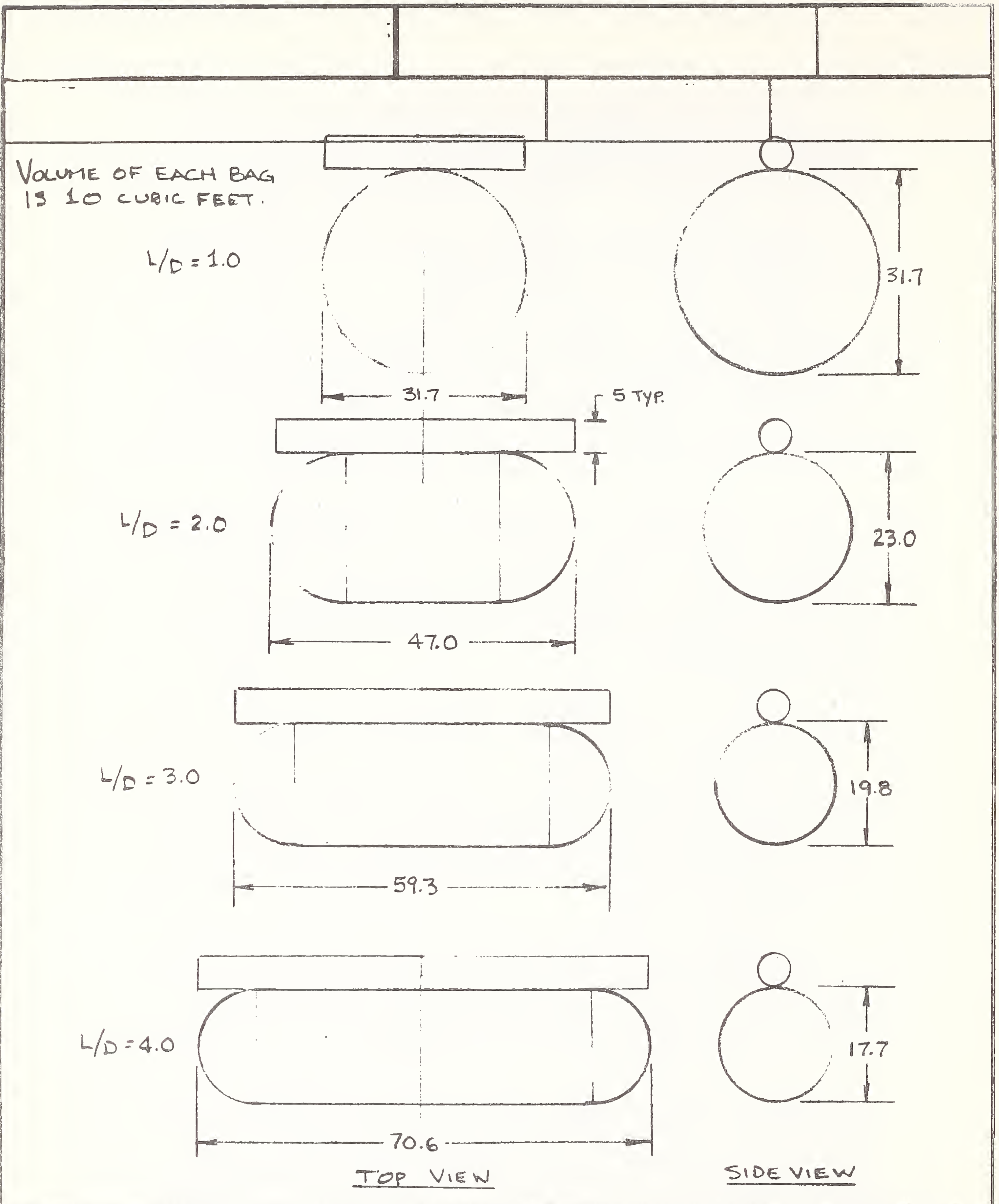
As the figure shows, the chest g's are very high for all three of the gas flow profiles so that there is no airbag/gas generator design possible that meets the 48 g goal with an L/D of 1.0 (a spherical airbag). Since the three gas flow profiles chosen for this study encompass practically all feasible gas flows for a ten cubic foot airbag, it is concluded that the spherical airbag has a shape that somehow seems to aggravate the out-of-position child. The question is, why?

The answer to this question becomes clearer as further results from the other runs with different L/D ratios are studied.

Figure 23 shows the results of the computer analysis after increasing the L/D ratio from 1.0 to 2.0, the latter which is, incidentally, the same airbag design used in the gas flow tailoring and the fabric weight analysis reported earlier. From this figure it can be seen that the peak check g's are somewhat lower so that a small zone of acceptable gas flow profiles exist which will meet the 48 g goal for the chest.

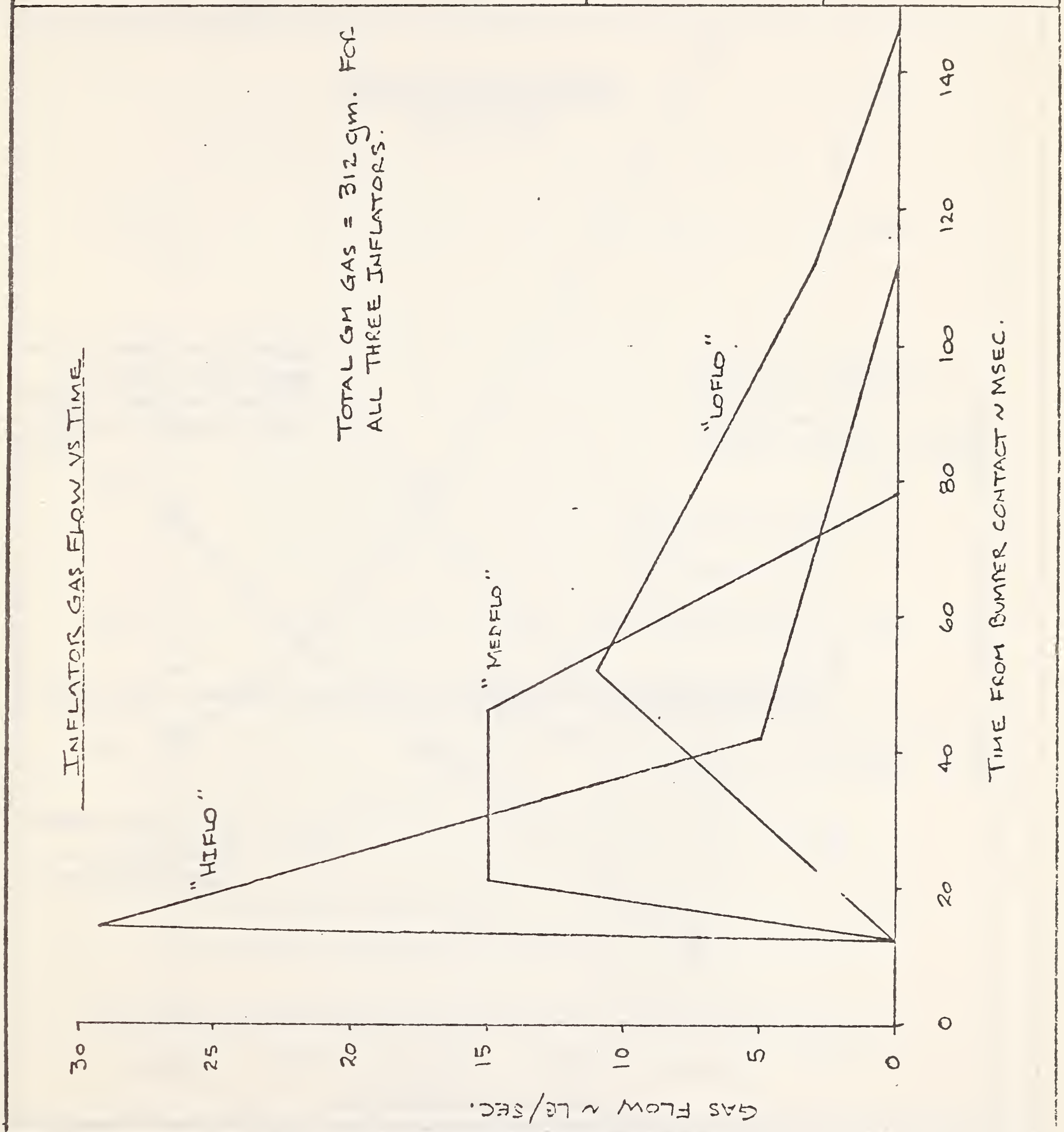
As the L/D ratio is increased still more, up to 3.0, it can be seen from Figure 24 that the chest g's drop even more so that the zone of acceptable gas flow profiles gets even larger, with a greater margin of safety between the 48 g goal for peak chest g's and the values actually realized. A pattern to the results obtained in the airbag shape study now begins to emerge.

As the L/D ratio is increased, the zone of acceptable gas flow profiles gets larger - effectively increasing the probability that a given inflator flow profile will satisfy the 48 g goal. Additionally, the margin between the actual peak chest g's and the 48 g goal gets more and more favorable as the L/D ratio increases and as the HIFLO type of gas generator is approached. The question, again, is why?



VOLUME OF EACH BAG IS 10 CUBIC FEET.
L/D = 1.0
31.7
31.7
5 TYP.
L/D = 2.0
23.0
47.0
L/D = 3.0
19.8
59.3
L/D = 4.0
17.7
70.6
TOP VIEW
SIDE VIEW

Figure 20.



INFLATOR GAS FLOW VS TIME
TOTAL GM GAS = 312 gm. FOR ALL THREE INFLATORS.
"HIFLO"
"MEDFLO"
"LOFLO"
GAS FLOW ~ LB/SEC.
0
5
10
15
20
25
30
TIME FROM BUMPER CONTACT ~ MSEC.
0
20
40
60
80
100
120
140

Figure 21.

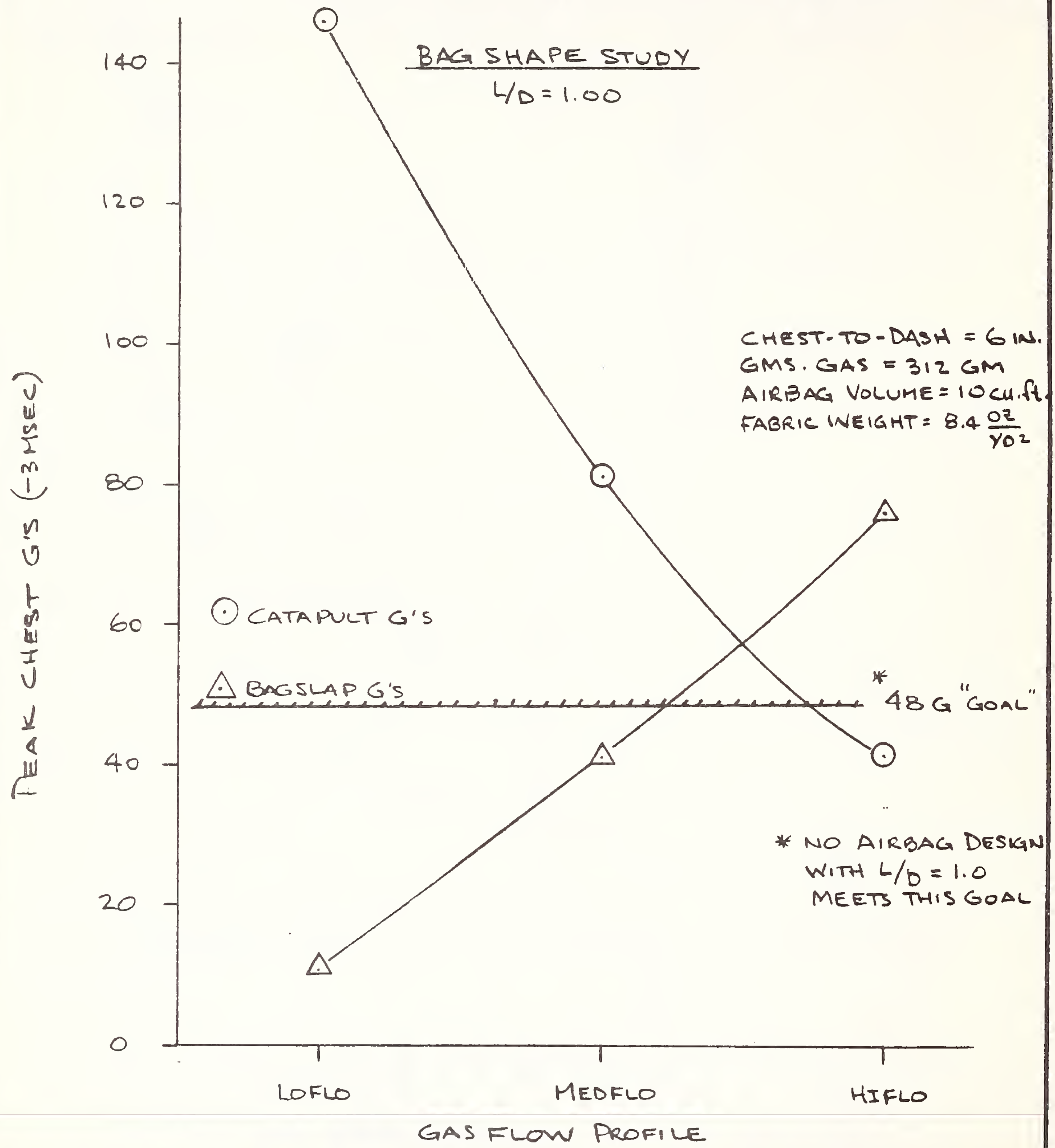
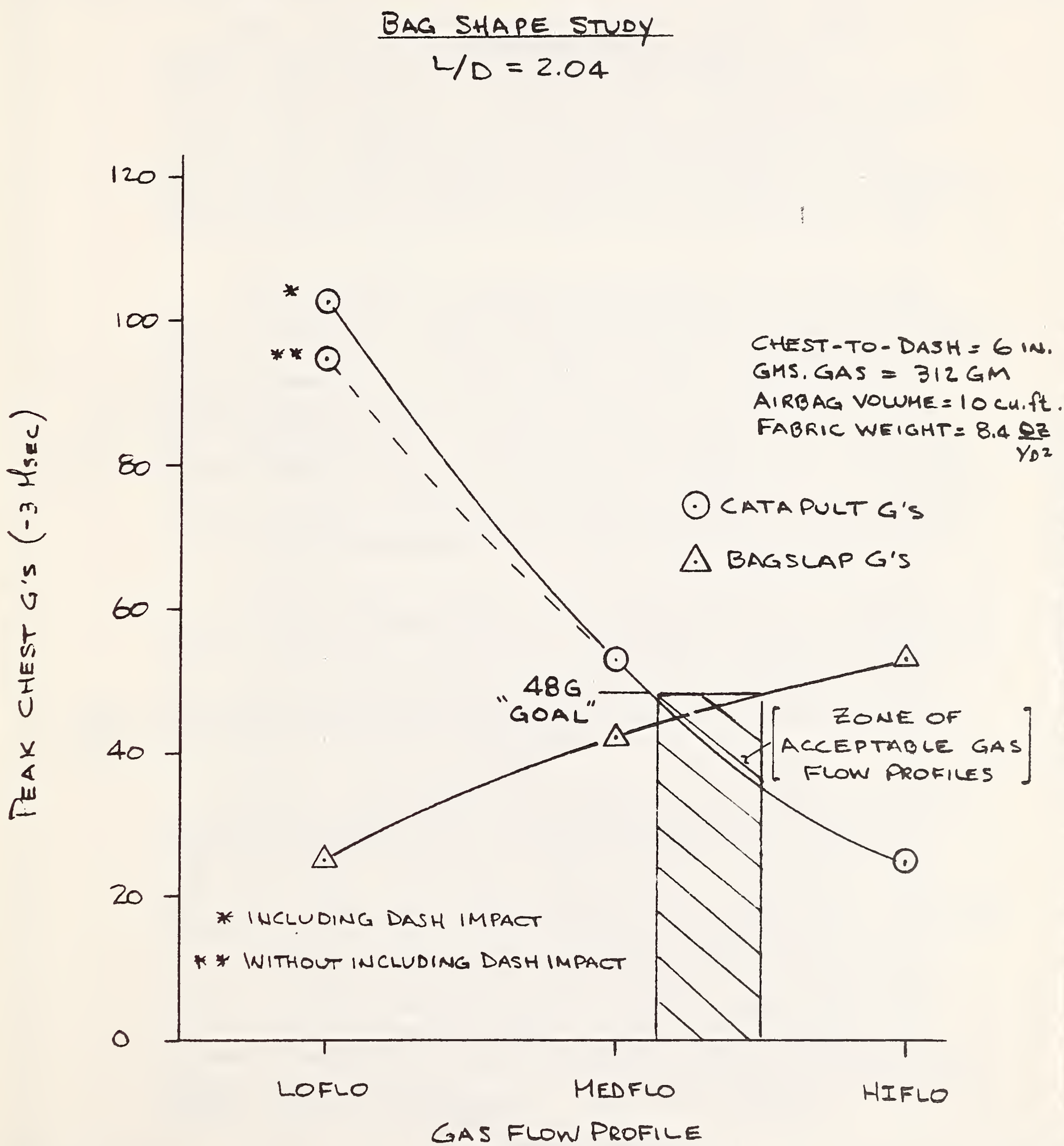
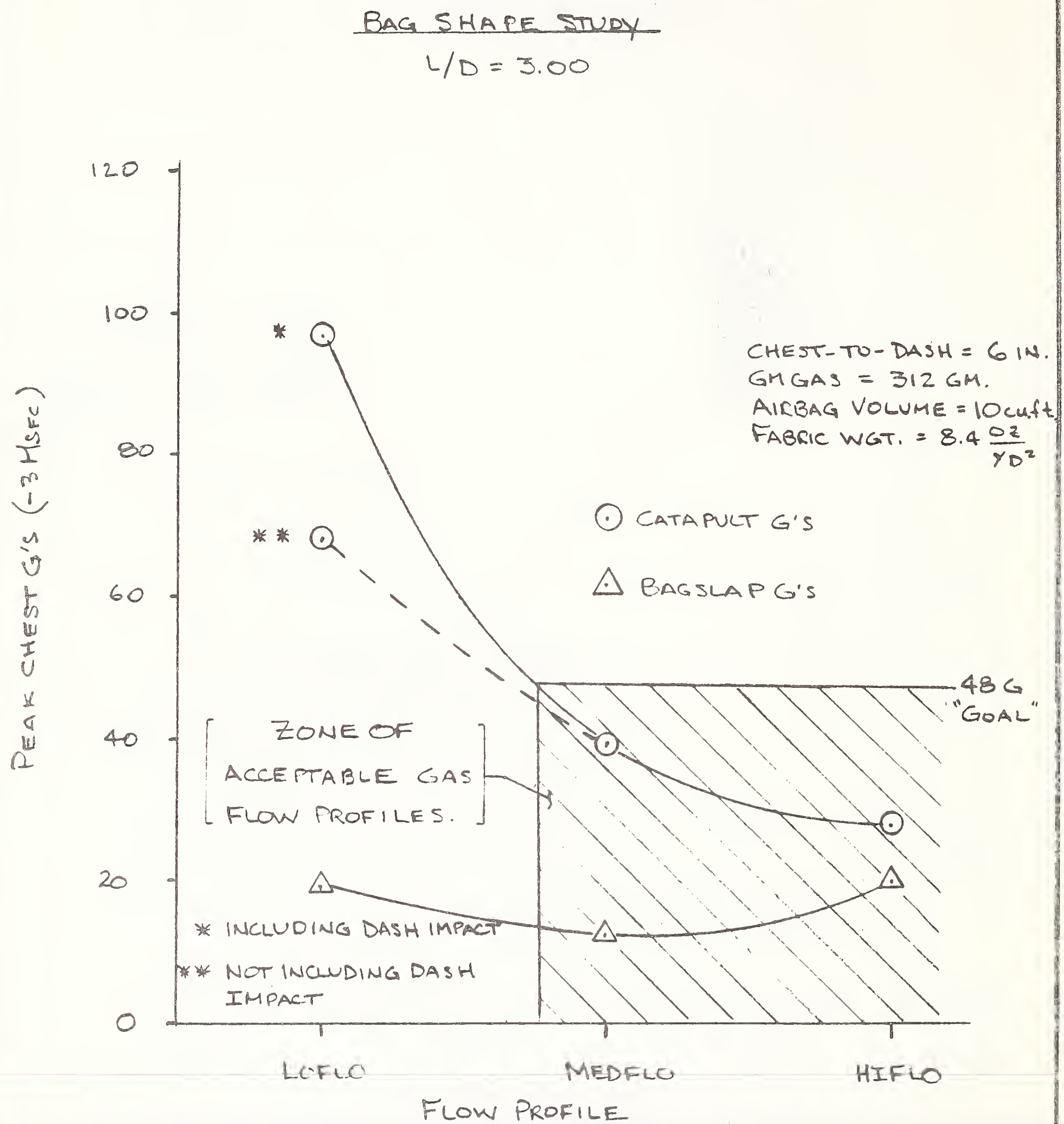

BAG SHAPE STUDY
L/D = 1.00
CHEST-TO-DASH = 6 IN.
GMS. GAS = 312 GM
AIRBAG VOLUME = 10 cu.ft.
FABRIC WEIGHT = 8.4 OZ/YD2
CATAPULT G'S
BAGSLAP G'S
* 48 G "GOAL"
* NO AIRBAG DESIGN WITH L/D = 1.0 MEETS THIS GOAL
PEAK CHEST G'S (-3 MSEC)
140
120
100
80
60
40
20
0
LOFLO
MEDFLO
HIFLO
GAS FLOW PROFILE

Figure 22.



BAG SHAPE STUDY
L/D = 2.04
120
100
80
60
40
20
0
PEAK CHEST G'S (-3 MSEC)
*
**
CHEST-TO-DASH = 6 IN.
GMS. GAS = 312 GM
AIRBAG VOLUME = 10 cu.ft.
FABRIC WEIGHT = 8.4 OZ/YD²
CATAPULT G'S
BAGSLAP G'S
48G "GOAL"
ZONE OF ACCEPTABLE GAS FLOW PROFILES
* INCLUDING DASH IMPACT
** WITHOUT INCLUDING DASH IMPACT
LOFLO
MEDFLO
HIFLO
GAS FLOW PROFILE

Figure 23.



BAG SHAPE STUDY
L/D = 3.00
120
100
80
60
40
20
0
PEAK CHEST G'S (-3 H_{SFC})
CHEST-TO-DASH = 6 IN.
GM GAS = 312 GM.
AIRBAG VOLUME = 10 cu.ft.
FABRIC WGT. = 8.4 OZ/YD²
CATAPULT G'S
BAGSLAP G'S
48 G "GOAL"
ZONE OF ACCEPTABLE GAS FLOW PROFILES.
* INCLUDING DASH IMPACT
** NOT INCLUDING DASH IMPACT
LOFLO
MEDFLO
HIFLO
FLOW PROFILE

Figure 24.

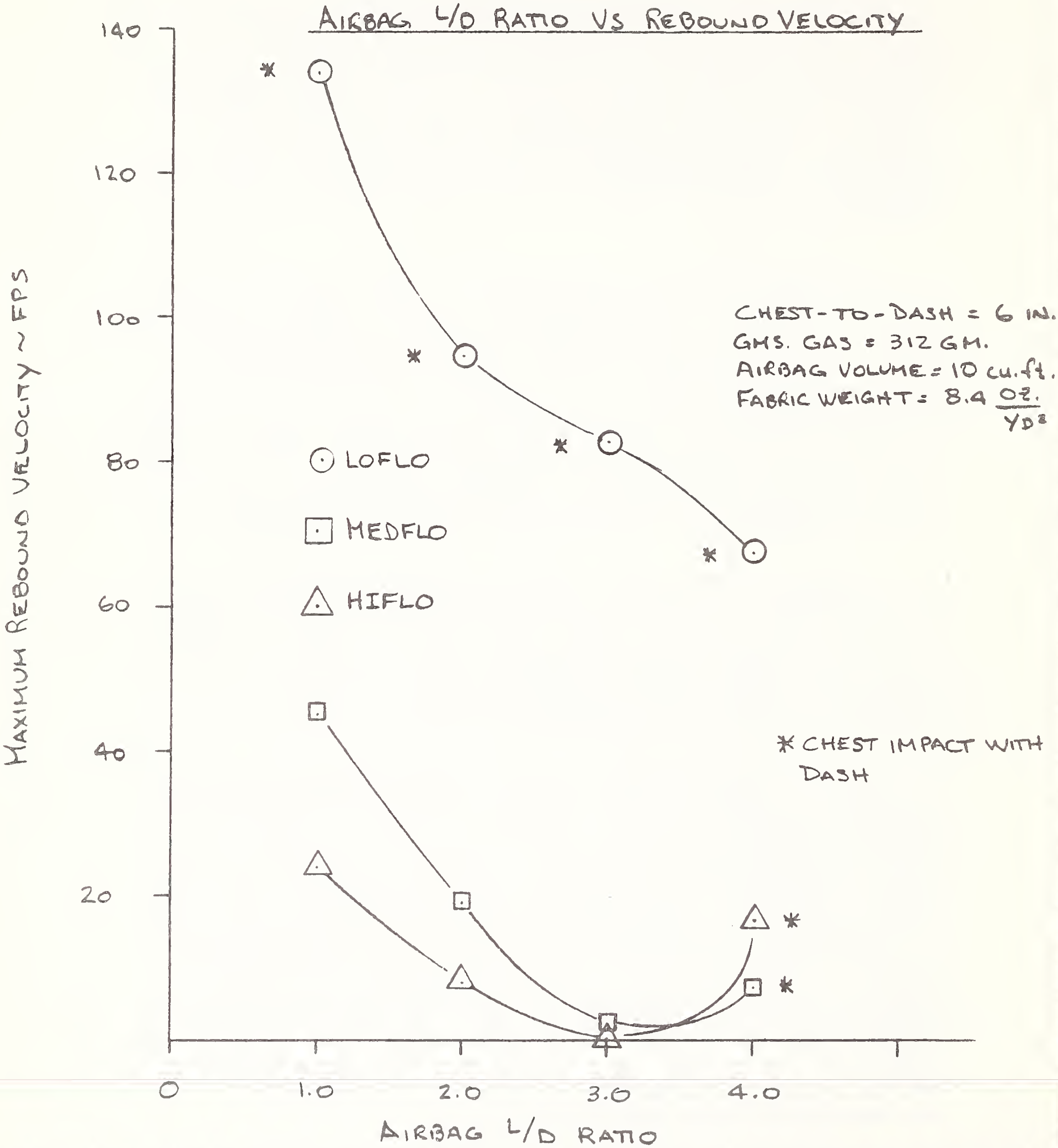
Upon studying the results of the computer runs, it emerges that three separate factors in the airbag design heavily influenced the peak chest g's.

First, it can be seen that the catapult g's are lowest for an airbag shape that is more elongated than spherical (higher L/D ratio). This is because, for a given airbag volume and chest-to-dash distance, the percent of the airbag depth penetrated by the child is greatest for the larger bag diameters (lowest L/D ratios). This results in the greatest wraparound forces being generated with correspondingly high catapult g levels. Conversely, when the bag is more elongated, a smaller percentage of total bag penetration occurs resulting in lower wraparound forces and lower catapult g's.

A second reason for the high catapult g's for low L/D ratios and, conversely, for the lower catapult g's for higher L/D ratios is that the greater the airbag diameter for a given airbag volume, the greater the degree of "pressure pumping" that is applied to the torso. By more "pressure pumping" it is meant that the airbag pressure forces are applied over a greater body length due to the greater airbag diameter. Since the airbag volumes and the total gas flow are held invariant for this part of the study, this means that the pressure forces are not much different for the different L/D ratios. However, since the bag diameter is different, the largest "pressure pumping" g's can be seen for the larger bag diameters due to the increased body length over which these forces operate.

A further effect of the larger bag diameters is that the pressure forces operate over a greater distance, imparting higher rebound velocities to the child. This effect is shown in Figure 25. The reason the rebound velocities tend to increase for an L/D of 4.0 for the HIFLO and MEDFLO cases is that the impact of the chest with the dash and subsequent rebound from the dash imparts an additional velocity during the rebound phase.

Thirdly, the bagslap g's are also lowest for high L/D ratios. The reason for this is that, for a given airbag volume, and the more elongated the airbag, the lower the percentage of the total bag width that impacts the chest. Since the constant volume criteria effectively means that each of the airbags has approximately the same total weight, this lower percentage of the total width of the airbag that impacts the chest means that the effective mass of the bag that impacts the chest is also reduced. Thus, for the more elongated airbags, less fabric mass is brought into direct chest contact. In the previous analysis it was shown that as the effective bag mass was increased, the peak chest g's would also increase for flow profiles like the MEDFLO and HIFLO flow profiles (Figure 4). Conversely, as the L/D ratio becomes smaller, more of the bag fabric is concentrated in front of the chest with correspondingly higher bagslap g's.



AIRBAG L/D RATIO VS REBOUND VELOCITY
MAXIMUM REBOUND VELOCITY ~ FPS
140
120
100
80
60
40
20
0
1.0
2.0
3.0
4.0
AIRBAG L/D RATIO
CHEST-TO-DASH = 6 IN.
GMS. GAS = 312 GM.
AIRBAG VOLUME = 10 cu.ft.
FABRIC WEIGHT = 8.4 OZ./YD²
LOFLO
MEDFLO
HIFLO
* CHEST IMPACT WITH DASH

Figure 25.

This latter discovery indicates that the bag should be folded so that the fabric is spaced out over as large an area as possible. In this way, the effective mass of the airbag that is closest to the chest is lowest. Further, we want a fairly elongated bag since more of the bag can be placed where the chest is not. And, finally, we want the more elongated bag so that the effect of "pressure pumping" and the magnitude of wraparound forces are minimized.

The L/D ratio was increased to 4.0 to see if this trend continued. As Figure 20 shows, the bag shape for L/D of 4.0 is not much different than for L/D of 3.0. Thus, as the L/D ratio is increased in steps of 1.0, less change in the general shape of the bag, is apparent.

The results of changing the L/D ratio to 4.0 are presented in Figure 26. Here the zone of acceptable flow profiles is almost the same as in Figure 24 for an L/D ratio of 3.0. However, one thing is quite different. Whereas in the case where the L/D ratio was 3.0 and the child impacted the dash only when the LOFLO flow profile was used, now the child impacts the dash for all three gas flow profiles. This says that the wraparound g's are now getting low enough that there is insufficient force generated to keep the child from going completely through the bag and impacting the dash. Thus even though the more elongated type of airbag seems to promise lowest injury measures for the out-of-position child, must be taken when designing the airbag not to go so far with increasing the L/D ratio that dash impact occurs for the child or for the normally seated adult.

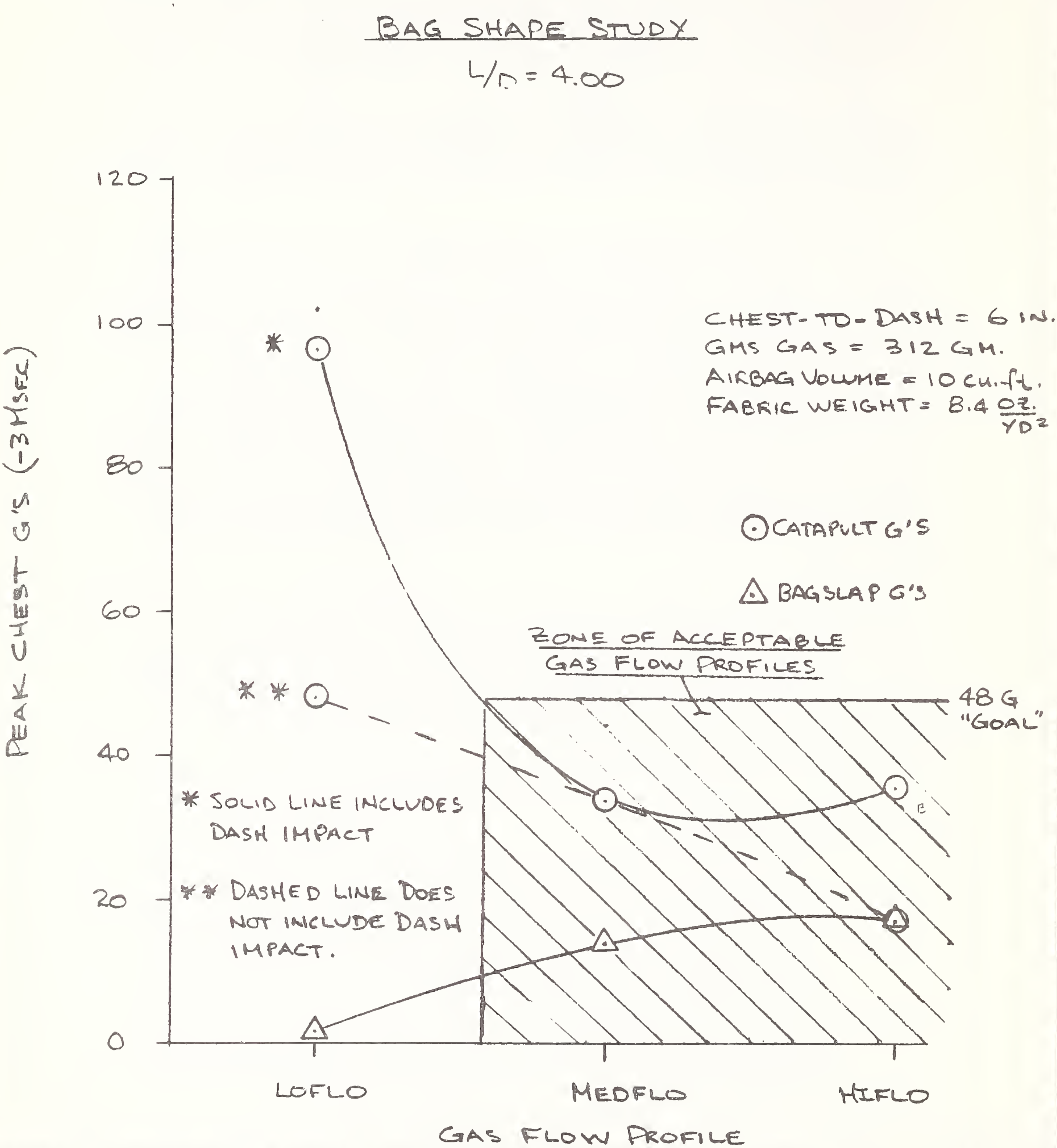
The results gained from this airbag shape study were very informative, pointing out the value of computer simulation in sorting out the competing mechanisms that determine out-of-position child reponse for various airbag/gas generator design combinations. Although the results seem reasonable once presented, they are, nevertheless, not intuitive enough to be arrived at without a computer type systems analysis.

Listed below are the main conclusions which may be drawn from the airbag shape study.

a) As the airbag length-to-diameter ratio is increased, the zone of acceptable gas flow profiles increases

b) As the airbag length-to-diameter ratio increases, the safety margin between the 48 g goal on chest g's and the actual value experienced increases

c) As the airbag length-to-diameter ratio is increased, the chances of the child going through the bag and impacting the dash increase



BAG SHAPE STUDY
L/D = 4.00
120
100
80
60
40
20
0
PEAK CHEST G'S (-3 MSEC)
CHEST-TO-DASH = 6 IN.
GMS GAS = 312 GM.
AIRBAG VOLUME = 10 CU. FT.
FABRIC WEIGHT = 8.4 OZ./YD²
CATAPULT G'S
BAGSLAP G'S
ZONE OF ACCEPTABLE GAS FLOW PROFILES
48 G "GOAL"
* SOLID LINE INCLUDES DASH IMPACT
** DASHED LINE DOES NOT INCLUDE DASH IMPACT.
LOFLO
MEDFLO
HIFLO
GAS FLOW PROFILE

Figure 26.

d) As the airbag length-to-diameter ratio is decreased, the bag becomes more concentrated in a location near the chest resulting in higher bagslap g's. This effect is most prounced for the more impulsive gas flow profiles such as MEDFLO and HIFLO. This indicates that the best bag fold would be one that concentrated most of the bag away from the child's chest; i.e. if the bag is folded along its entire width and if that width is relatively long, bagslap g's will be lowest.

e) As the airbag length-to-diameter ratio decreases, there is a larger contact area on the child's chest resulting in higher catapult g levels. Also, the greater depth of airbag results in a greater pressure stroke and correspondingly higher rebound velocities.

f) Because of the above listed factors, it appears that an airbag with internal "tethers" would perform well with the forward positioned child. This type of bag would also accomodate the widest variety of gas flow profiles and still meet the injury criteria. However, care must be exercized not to overly compromise the ridedown performance for the adult occupants

g) The MEDFLO and HIFLO gas flow profiles are preferred over the slower LOFLO type of flow profile since the LOFLO profile has a tendency to allow the chest to impact the dash. Further, the lack of "ridedown" inherent in this type of generator results in high, late peaking chest g levels when an attempt is made to prevent dash impact.

4.4 Effect of Airbag Volume

Following the investigation into the effect of airbag shape on the forward positioned child's dynamic response, a related, but somewhat different area of the sensitivity analysis was pursued. This was the investigation of the effect the deploying airbag total volume has on the out-of-position child response.

4.4.1 Methodology

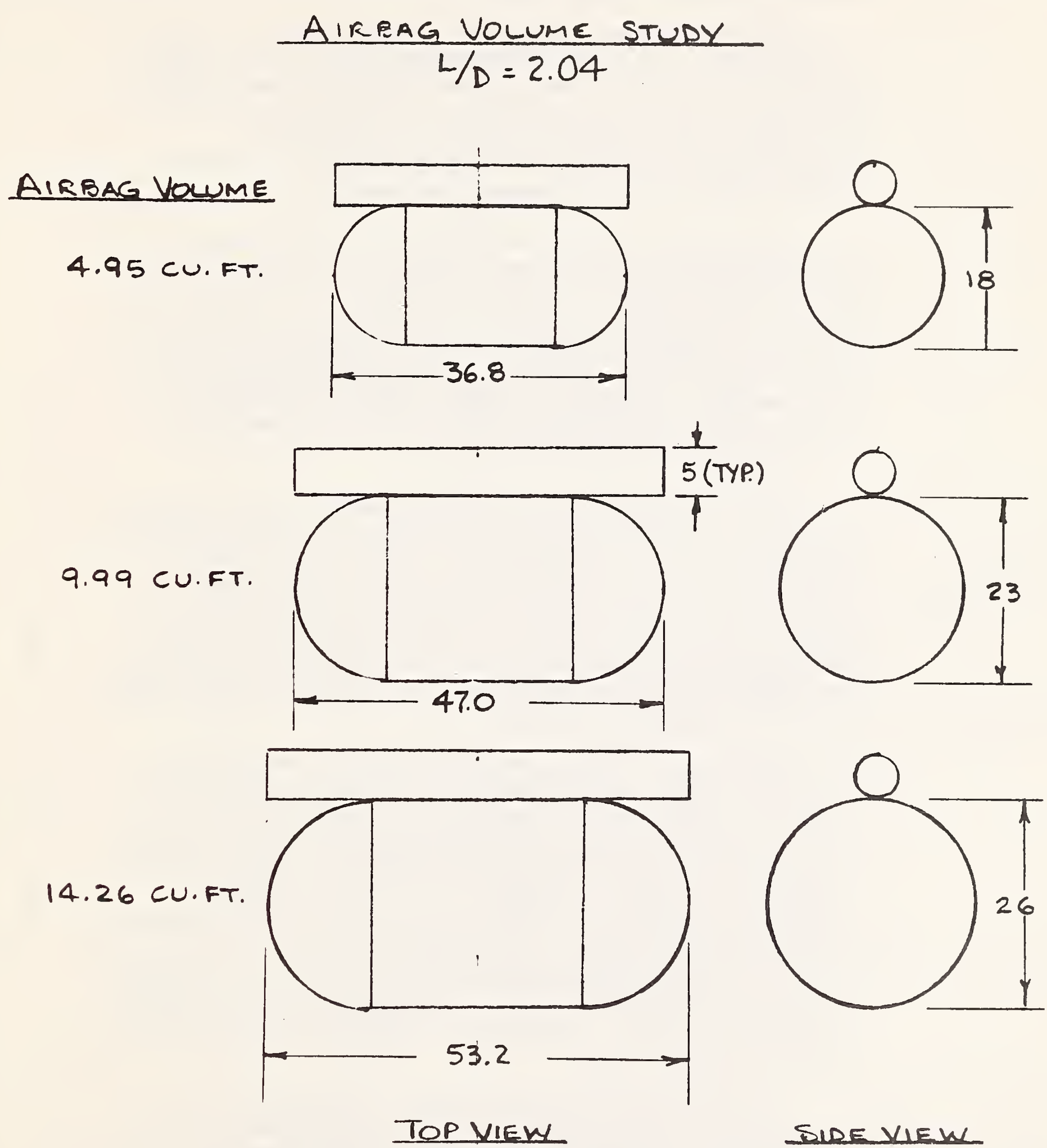
For this investigation, as in the previously reported investigations, the "LOFLO," "MEDFLO" and "HIFLO" gas flow profile types were used as the standards of reference. However, since the volume was to be varied, it was necessary to multiply the gas flow rates shown in Figure 4 by the volume ratio equal to the new volume divided by the reference airbag volume of 10 cubic feet which has been used throughout the analysis up to this point. By doing this the total grams of generated gas per cubic foot of airbag volume was kept constant at 31.2 grams per cubic foot - the value established in Section 4.2 as appropriate for a vehicle in the Citation weight class.

It was also necessary to establish the airbag vent area that would be used with each flow profile and airbag volume. In order to accomplish this, for each volume within each flow profile investigated, DEPLOY was run and rerun with the normally seated adult varying the vent area until the 50th percentile male would penetrate the airbag to approximately 75 percent of the total depth available at the point of maximum penetration. This vent area then became the vent area used for the corresponding case in the child simulations.

All parameters other than airbag volume and gas flow profile with its associated vent area were held constant. These constant variables included the airbag length-to-diameter ratio at 2.04, the chest-to-dash distance at 6 inches, the fabric weight at 8.4 ounces per square yard, the total grams of gas per cubic foot of airbag volume at 31.2, and the crash environment of a frontal barrier impact of the Citation at 30 mph.

4.4.2 Bounding the Problem - Airbag Volume

Figure 27 shows the range over which the airbag volume was varied. The airbag volume used in this study up to this point was 10 cubic feet and comprised the middle of the range of volumes investigated. In all, three different volumes were compared; 5.0 cubic feet, 10.0 cubic feet, and 14.3 cubic feet. As previously



Airbag Volume Study

Figure 27.

mentioned, the airbag length-to-diameter ratio was held constant at 2.04 so that the airbags had the same overall shape as shown in Figure 27.

4.4.3 Results - Airbag Volume Study

Figures 28 and 29 show the results from the airbag volume study. The two figures divide the results into bagslap g's versus airbag volume (Figure 28) and catapult g's versus airbag volume (Figure 29). The reason for dividing up the results this way is a matter of convenience so the different aspects of the effect of airbag volume can be discussed separately.

Figure 28 shows the bagslap g's for the forward positioned child plotted as a function of airbag volume. As is evident from the figure, bagslap g's increase with increasing airbag volume for the MEDFLO and HIFLO gas flow profiles, while the bagslap g's are relatively constant for all three volumes for the LOFLO gas flow profile. Additionally, for a given airbag volume, the bagslap g's increase with increasing rates of initial flow onset as one proceeds from LOFLO to HIFLO.

All this should sound somewhat familiar for these are precisely the effects noted for increasing fabric mass reported earlier in Section 4.1. Upon close inspection of the results it can be seen that the phenomenon that appears here in the guise of an airbag volume effect, is really another manifestation of the fabric mass effect. One might well wonder how this could be since the fabric mass has been held constant for the airbag volume study at 8.4 ounces per square yard.

The answer lies in the fact that the larger airbag volumes, having larger diameters, result in a greater weight of airbag fabric per inch of airbag width. Thus, as the airbag volume is increased from five cubic feet to fourteen cubic feet for constant L/D, the airbag diameter increases as shown in Figure 27. As this diameter increases, there is, in both the stowed and the deploying airbag configurations, more fabric mass per inch of airbag width with correspondingly higher bagslap g's. Therefore, the effect noticed here under the airbag volume stuay is nothing more than a reappearance of the effects of fabric mass on bagslap g's.

It should be noted here that a "rolled up" type of bag fold is assumed in the computer program as formulated. If a more "accordian" type of bag fold were used where only the front of the deploying airbag came into chest contact, this effect could be much reduced or

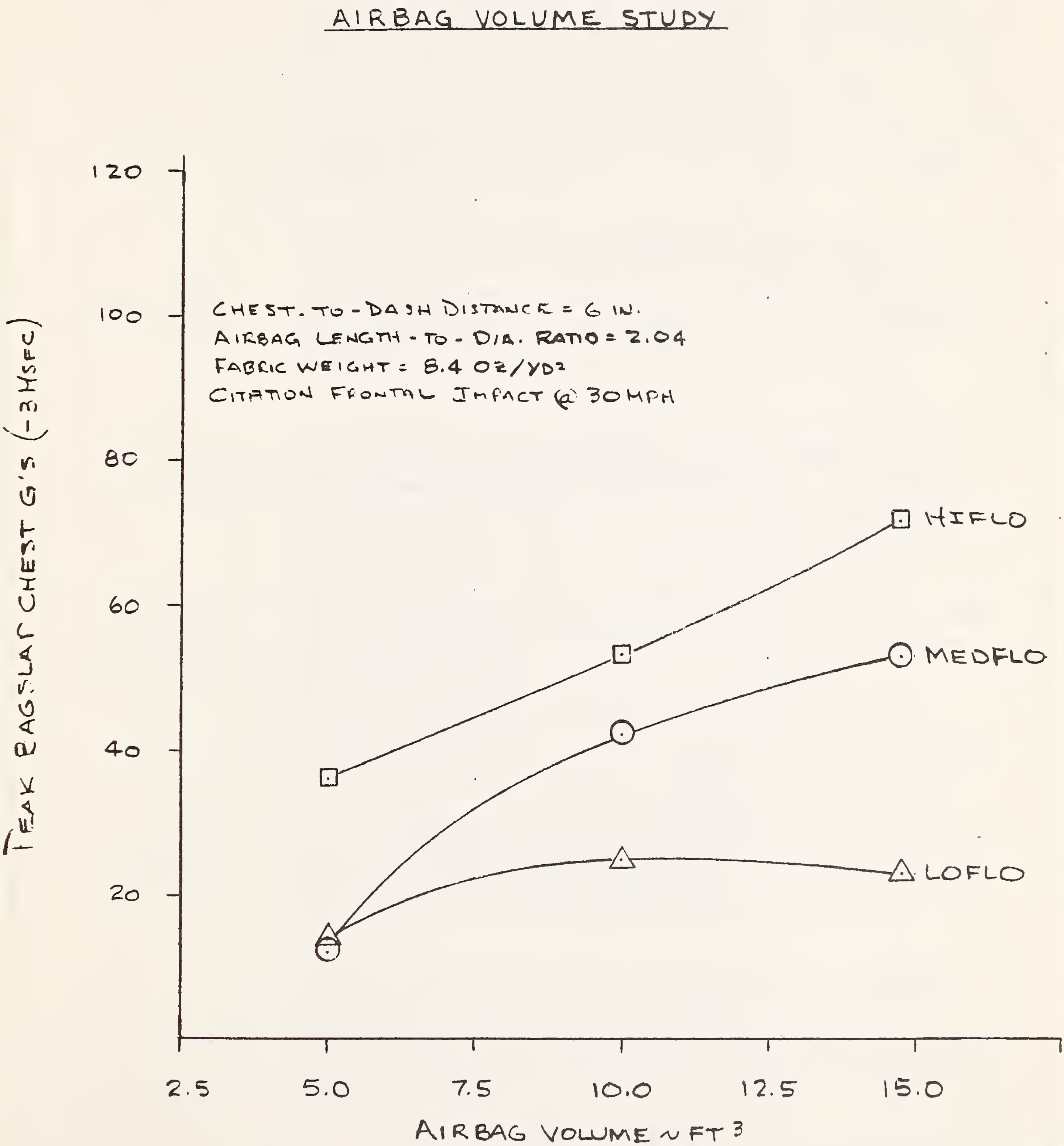


Figure 28.

CHECKED BY

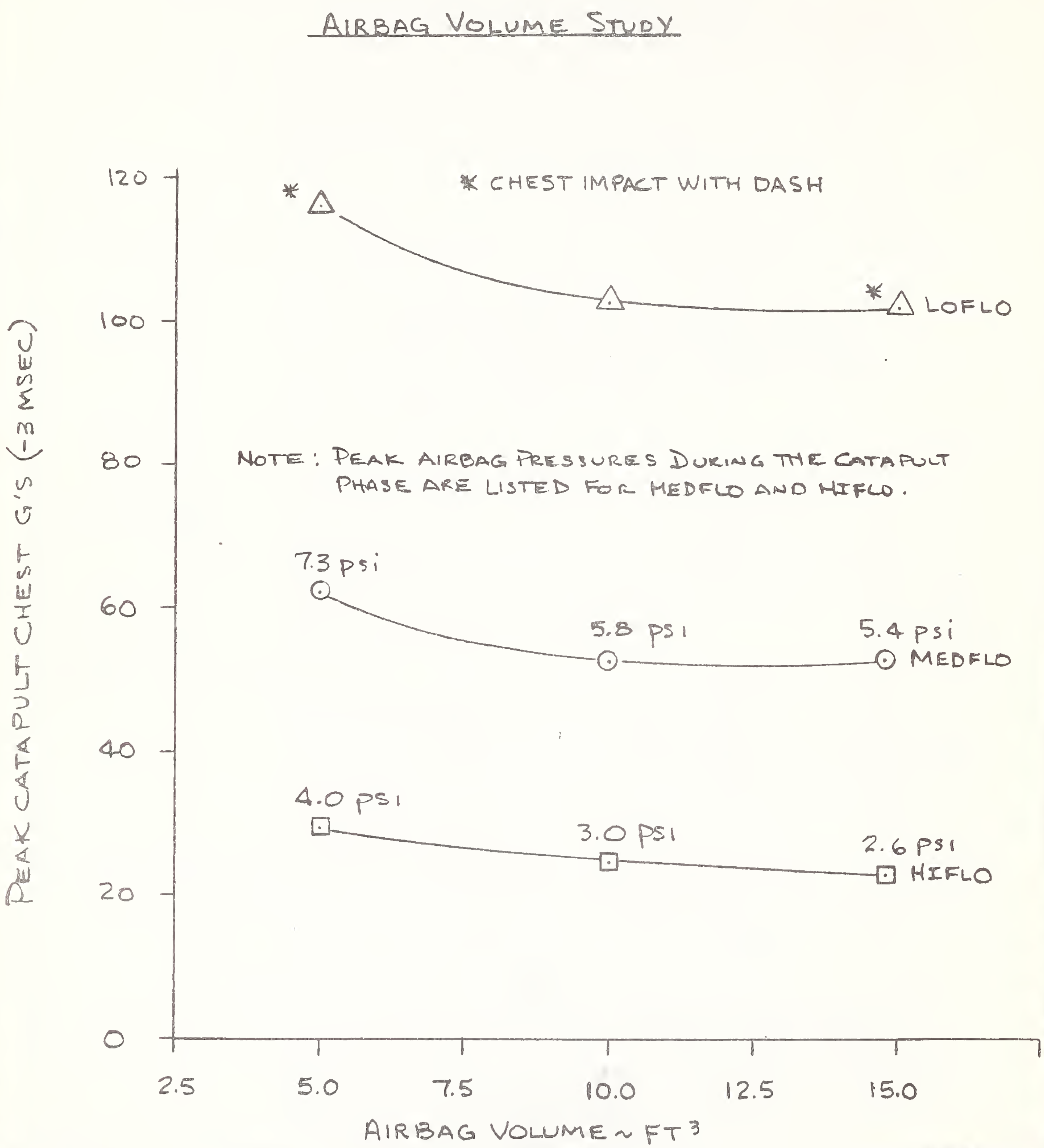

AIRBAG VOLUME STUDY
* CHEST IMPACT WITH DASH
LOFLO
NOTE: PEAK AIRBAG PRESSURES DURING THE CATAPULT PHASE ARE LISTED FOR MEDFLO AND HIFLO.
7.3 psi
5.8 psi
5.4 psi
MEDFLO
4.0 psi
3.0 psi
2.6 psi
HIFLO
PEAK CATAPULT CHEST G'S (-3 MSEC)
0
20
40
60
80
100
120
2.5
5.0
7.5
10.0
12.5
15.0
AIRBAG VOLUME ~ FT³

Figure 29.

possibly eliminated. The DEPLOY program is flexible enough to accept other fold patterns, but for this study, the rolled technique was used to give the most conservative results.

Let us now discuss the effect of airbag volume on catapult g's as presented in Figure 29. In this figure we have plotted catapult g's for the forward positioned child versus airbag volume. In this figure it can be seen that all three curves are qualitatively the same showing very little effect of airbag volume on catapult g's for a given gas flow profile - although there is a great difference in catapult g's between the gas flow profiles for a given airbag volume.

First, the effect of catapult g's as a function of airbag volume will be discussed. As the airbag volume is increased fom five cubic feet, a lessening effect of airbag volume on catapult g's is evident up to ten cubic feet. After this point, increasing the airbag volume still more toward fourteen cubic feet results in practically no difference at all.

The reason for this is as follows. As previously mentioned, in order to obtain results for the out-of-position child that were as accurate as possible, DEPLOY was run and rerun with the normally seated adult for each flow profile and for each airbag volume within each flow profile until a vent area was established for each set of conditions that would allow the 50th percentile male a maximum airbag penetration of approximately 75 percent of the total airbag depth. This would still leave enough additional depth to handle the 95th percentile male. Throughout these adult simulations, a constant chest-to-dash distance of 21 inches was maintained. Thus, for the smaller airbag volume of five cubic feet with an airbag diameter of only 18 inches (Figure 27), the adult passenger had a three inch gap between his chest and airbag at full deployment.

Conversely, for the largest airbag volume of fourteen cubic feet with a diameter of 26 inches, there are 5 inches of initial airbag penetration. The significance of this factor will become apparent in the following discussion.

Once the vent area was established for each airbag volume (5, 10 and 14 cubic feet) within each gas flow profile for the adult, simulations of the forward positioned child could begin using these same vent areas for the corresponding conditions of airbag volume and gas flow profile.

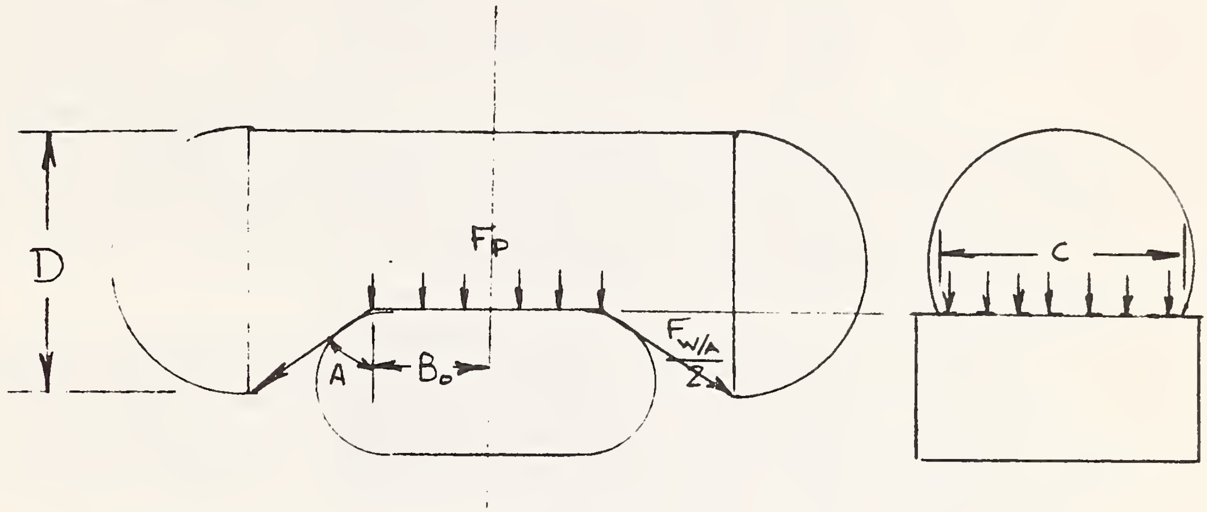
Consider now the two equations presented with Figure 30. The first equation describes in approximate terms the variables governing the wraparound forces. The second equation describes the pertinent factors influencing the pressure forces. Consider the effect on these equations as the volume is increased from the 5 cubic foot value up to the 14 cubic foot value.

First, when the airbag volume is 5 cubic feet, the normally seated adult's chest is, as previously described, 3 inches rearward of the fully deployed airbag's rearmost surface. This means that valuable time is wasted as the adult closes this gap during the crash. As a result, the amount of the passenger's kinetic energy absorbed in the efficient "ridedown" mode is low and the airbag itself must absorb a preponderent amount of the energy through airbag penetration. Thus, for a given total allowed penetration for the adult of 75 percent of the 18 inch airbag diameter, the required vent area is relatively small and the resulting airbag pressure relatively high.

However, as the airbag volume is increased, the airbag diameter gets larger and the initial wraparound effects increase with a larger and larger amount of the passenger energy absorbed in the ridedown mode with less energy required to be absorbed by penetrating the airbag. Therefore, for a constant airbag penetration of 75 percent of the total airbag depth, it can be seen that the larger the airbag volume the lower the requied airbag pressure.

Now consider the child in light of the equations presented in Figure 30. Since the required airbag pressures for the adult decrease with an increase in airbag volume, they will do the same for the child since he has the same gas flow profile and the same vent area. From the equations then, it can be seen that an increase in airbag volume and the resulting decrease in pressure will tend to <u>reduce</u> both the wraparound and the pressure forces being applied to the child. However, as we increase the volume, both the "D" and "C" terms in the equations also increase which tends to cause a net <u>increase</u> in the forces. Thus, an increase in airbag volume will result in countering effects; the pressure goes down but the bag diameter and the body intercept length go up.

Therefore, the explanation for the relatively slower rate of drop off in chest g's as the volume gets progressively larger is explained by the pressure effect being predominant at the smaller volumes but this effect being offset by the "D" and "C" terms as the volume gets still larger. This explains the relatively constant value



1) $F_{W/A} \cong \dfrac{PDC\cos A}{2}$

2) $F_P \cong 2PCB_o$, WHERE :

$F_{W/A}$ = WRAPAROUND FORCE

F_P = PRESSURE FORCE

P = AIRBAG PRESSURE

C = LENGTH OF AIRBAG IN CONTACT WITH CHEST.

D = INSTANTANEOUS AIRBAG DIA.

A = WRAPAROUND ANGLE

B_o = HALF WIDTH OF CHEST

Figure 30.

for chest g's for volumes between 10 and 14 cubic feet as the declining pressure is offset by the increasing bag diameter and chest contact length (the "D" and "C" terms respectively).

The effect of the gas flow profile on chest response for constant airbag volume will now be discussed.

Going from the HIFLO to the LOFLO gas flow profile type, it can be seen from Figure 29 that the catapult chest g's increase significantly. This is not surprising since, as was discussed in the section on the effects of gas flow tailoring, the more impulsive gas flow profiles such as HIFLO (and to a lesser extent, MEDFLO) result in more of the child's energy being absorbed in the efficient ridedown mode. Thus the g-profile on the child's chest is of relatively long duration and relatively constant as compared to the LOFLO case.

The LOFLO gas flow profile, on the other hand, with its relatively slow flow onset that gradually builds to its highest flow rate late in the crash event, results in relatively slow airbag deployment with an airbag pressure that peaks late. For this reason, the chest g's are also late peaking and very high.

Probably more time has been spent explaining the effect airbag volume has on the catapult chest g's than would be deserved considering the relatively small variation in catapult g's with airbag volume that actually exists. However, even though the overall effect may be somewhat inconsequential, the explanation given here for what little effect there is increases the understanding of the factors that influence the out-of-position child response. It also gives us an appreciation for the parameters which are important and which are relatively unimportant as they affect the overall injury measures received by the forward positioned child.

Listed below are our conclusions for the effect of airbag volume on the dynamic response of the out-of-position child.

a) Overall it may be stated that the effect of airbag volume on the out-of-position child is relatively minor. As stated above, there are related effects due to increased fabric mass that result from an increase in volume that appear to be due to a volume effect, but these can be shown to be primarily the result of previously identified effects other than airbag volume such as total fabric mass.

b) The role of airbag volume in airbag design for the forward positioned child or the normally seated adult is therefore more a matter of the practical considerations of available space in the vehicle, such as, whether the vehicle has bench or bucket type seats (must support more than one passenger or not), distance of the chest from the dash in the normally seated configuration, and whether the system is high or low mount. As stated above, the airbag volume considerations alone appear to be relatively minor for the forward positioned child.

c) Again, the preferred gas flow profile for best overall performance would be of the HIFLO-MEDFLO type; this would be true for the entire range of volumes investigated. This would indicate that for the best overall out-of-position child performance and, for that matter, best normally seated adult performance in the subcompact car crash environment, we would use the more impulsive type gas flow profile - a direction generally opposite to that taken in most experimental programs. If a less impulsive flow profile is chosen, then it would help if either the bag were designed with internal tethers or otherwise constrained from bringing the full catapult forces to bear on the child. In this way perhaps the high, late peaking catapult forces typical of the LOFLO type gas flow profile could be attenuated.

4.5 Effects of Aspiration and Gas Dumping

In considering technical options to attenuate bagslap for the out-of-position child by somehow dumping a portion of the gas in the airbag if the airbag pressure exceeded some predetermined threshold amount was considered. The idea was based upon the hypothesized possibility that the airbag pressure might have a maximum value that would be higher for the forward positioned child than for the normally seated adult. If it turned out this were true, then a method whereby a vent would dump gas out of the airbag once some design pressure were reached would in effect limit the g level on the chest. Naturally for this to work properly, the maximum pressure that the bag would "try" to attain must be greater for the out-of-position child case than for the normally seated passenger case; otherwise, the bag would dump the gas for the case where the passenger was seated normally. Therefore, in order to work properly, if the normally seated passenger occupied the passenger seat, no gas dumping would occur; if however, the forward

positioned child occupied the passenger seat and the pressure were sufficiently high, the gas would dump and the chest g's would presumably be reduced.

In order to investigate this possibility, a series of six computer runs were made - three each with the out-of-position child and the normally seated adult. Three runs were made for each seating configuration in order to investigate three separate gas flow profiles and their effect on the potential for "gas dumping." The three gas flow profiles used were shown in Figure 4 which were used extensively in the rest of the study.

Table 2 lists the pertinent results of these simulations. In all six runs the fabric weight was held constant at 8.4 ounces per square yard and the chest-to-dash distance constant at six inches.

Table 2
Pressure Dump Study

Flow Type	Normally Seated Adult Peak Pressure -psi-	Out-of-Position Child Peak Pressure -psi-
LOFLO	16 psi at 100 msec for 25 msec.	10 psi at 100 msec for 15 msec.
MEDFLO	12 psi "spike" before bagslap, then 6 psi for 15 msec at 65 msec.	12 psi "spike" before bagslap, then 6 psi for for 10 msec at 60 msec.
HIFLO	35 psi "spike" before bagslap, then 3 psi for 30 msec at 50 msec.	35 psi "spike" before bagslap, then 3 psi for 10 msec at 45 msec.

The "gas dumping" possibility for attenuating the bagslap chest g's does not appear promising based upon these results.

First of all, in the case where the LOFLO gas generator is used, the airbag pressures with the adult are even higher than with the child. This is hardly the situation we need to trigger gas dumping for the forward positioned child.

Secondly, the peak pressures in the MEDFLO and HIFLO cases are reached <u>before</u> airbag contact with the chest. This means there is no pressure discrimination possible between the forward positioned child case and the normally seated adult case.

We therefore conclude that gas dumping based upon reaching a threshold airbag pressure is not a promising method of reducing injury for the out-of-position child.

A similar situation occurs with aspiration techniques. In fact, aspiration is a specific type of pressure dumping or flow redirection depending on the terminology preferred.

When an aspirated inflator system begins to inflate a bag in front of a normally seated occupant, the flow stream pressures are designed such that a secondary aspirated flow is set-up which augments the mass flow in the primary stream. However, when an obstruction to the bag deployment is encountered, the main gas stream is redirected (dumped) resulting in a stalling of the aspirating flow process.

There have been claims made about the benefits of aspirating to attenuate bagslap g's. However, based on the DEPLOY analysis and reviewing much experimental data, the benefits of aspirating to reduce injury potential for the out-of-position child from bagslap would be minimal. This is because (as the gas dumping analysis showed) by the time the bag first contacts the forward positioned child's chest, the energy in the bag, and the flow energy behind it, is already set at a value which will predetermine the degree of bagslap which the child will experience. Only after the bagslap event is over will flow redirection and aspiration stalling occur. Thus, the requirement for crash protection ridedown and inflation times for the normally seated occupant will determine the initial inflation rate up until the bag would impact any out-of-position child's chest. This fixes the bagslap response regardless of any aspirating later in the event.

It is true that the flow redirection (gas dumping) of the aspiration techniques will reduce the catapult phase g's should a child's chest be encountered during deployment and this reduction can, in turn, be traded off - much as in the mass flow tailoring discussion - to lower the bagslap g's. It does not appear however, that making this tradeoff with the aspiration technique has any advantage over making the tradeoff directly with the use of mass flow tailoring or dual level systems, or both.

Aspirators may have other benefits including minimizing propellant requirements and system weight but, based on this analysis and much developmental experience, aspiration will not have an inherent advantage over the most advanced direct flow systems in reducing out-of-position child bagslap g's.

4.6 Effects of Chest-to-Dash Distance

4.6.1 Bounding the Problem

The final parameter investigated as part of this study was what effect the distance of the child's chest

from the dash at the time of vehicle impact had on the degree of injury which it receives. Parameters held constant for this portion of the study were:

a) Crash environment of the Chevrolet Citation in a 30 mph frontal impact

b) Airbag volume - 10 cubic feet

c) Airbag length-to-diameter ratio - 2.04

d) Airbag fabric weight - 8.4 oz. per sq. yd.

e) Total mass of gas flowing into airbag - 312 gm.

f) Three-year-old child anthropometric properties.

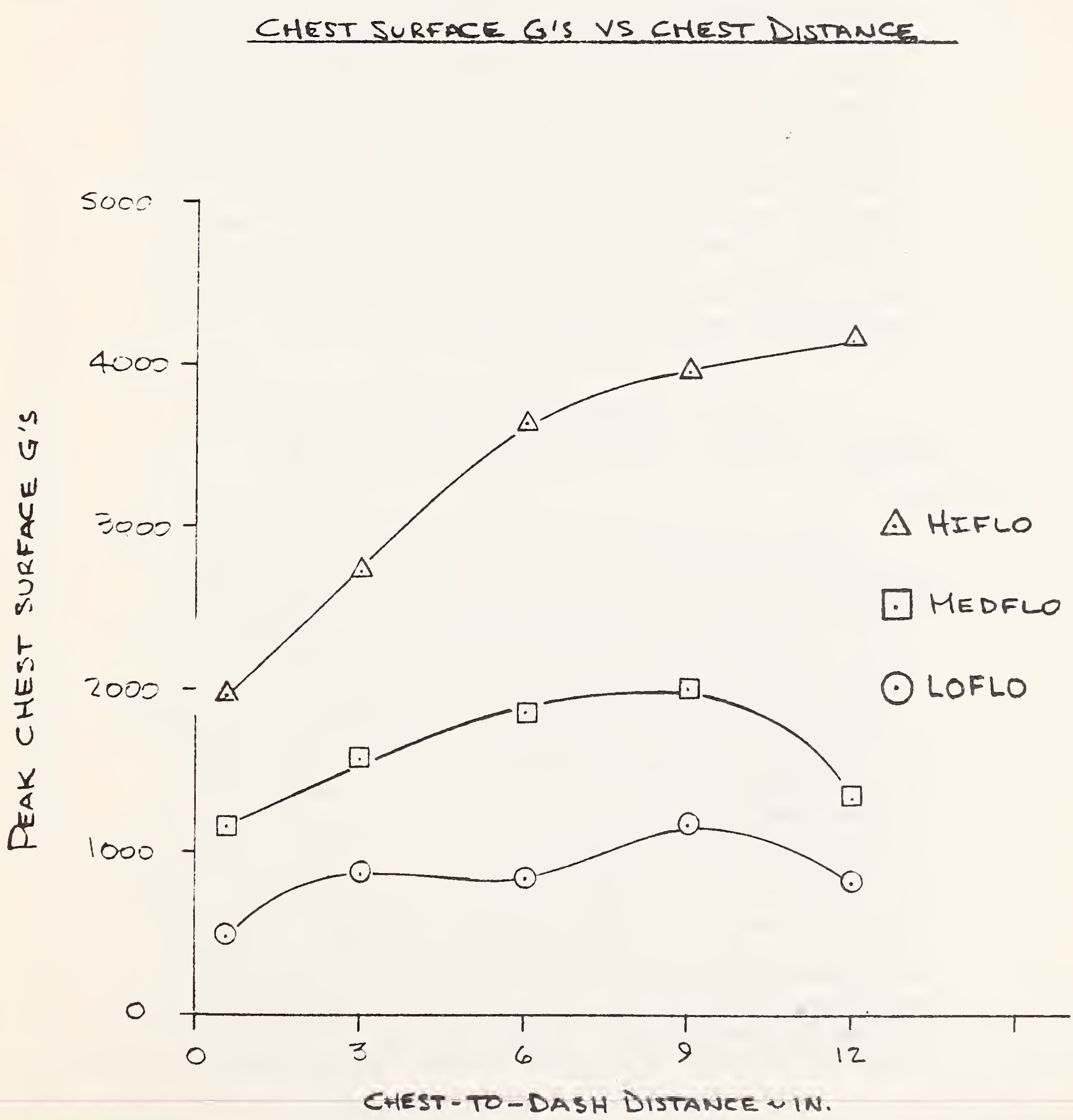
Paramenters varied in the study were the chest-to-dash spacing and the gas flow profile. The gas flow profiles used were the LOFLO, MEDFLO and HIFLO profiles as shown by Figure 4. For each of these three gas flow profiles, chest-to-dash distances of 0.5, 3.0, 6.0, 9.0, and 12.0 inches were investigated.

4.6.2 Results - Chest-to-Dash Spacing

Again, it is convenient to discuss the results of the study in two parts - the bagslap phase and the catapult phase. We will first discuss the effect of chest-to-dash spacing on bagslap g's.

For all five distances studied, the 3 msec clipped values for the main chest (spinal) g's (as opposed to the chest surface g's) were below the criteria limit of 60 g's. The most information about the effect of the chest-to-dash distance on bagslap g's may be obtained by studying the behavior of the chest surface (sternal) g's.

Figure 31 shows a plot of absolute peak chest surface g's plotted versus the initial chest-to-dash distance. As can be seen from the figure, the bagslap g's on the chest surface dramatically increase with increasing rates of gas flow into the airbag proceeding from the LOFLO gas flow



CHEST SURFACE G'S VS CHEST DISTANCE
PEAK CHEST SURFACE G'S
5000
4000
3000
2000
1000
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
HIFLO
MEDFLO
LOFLO

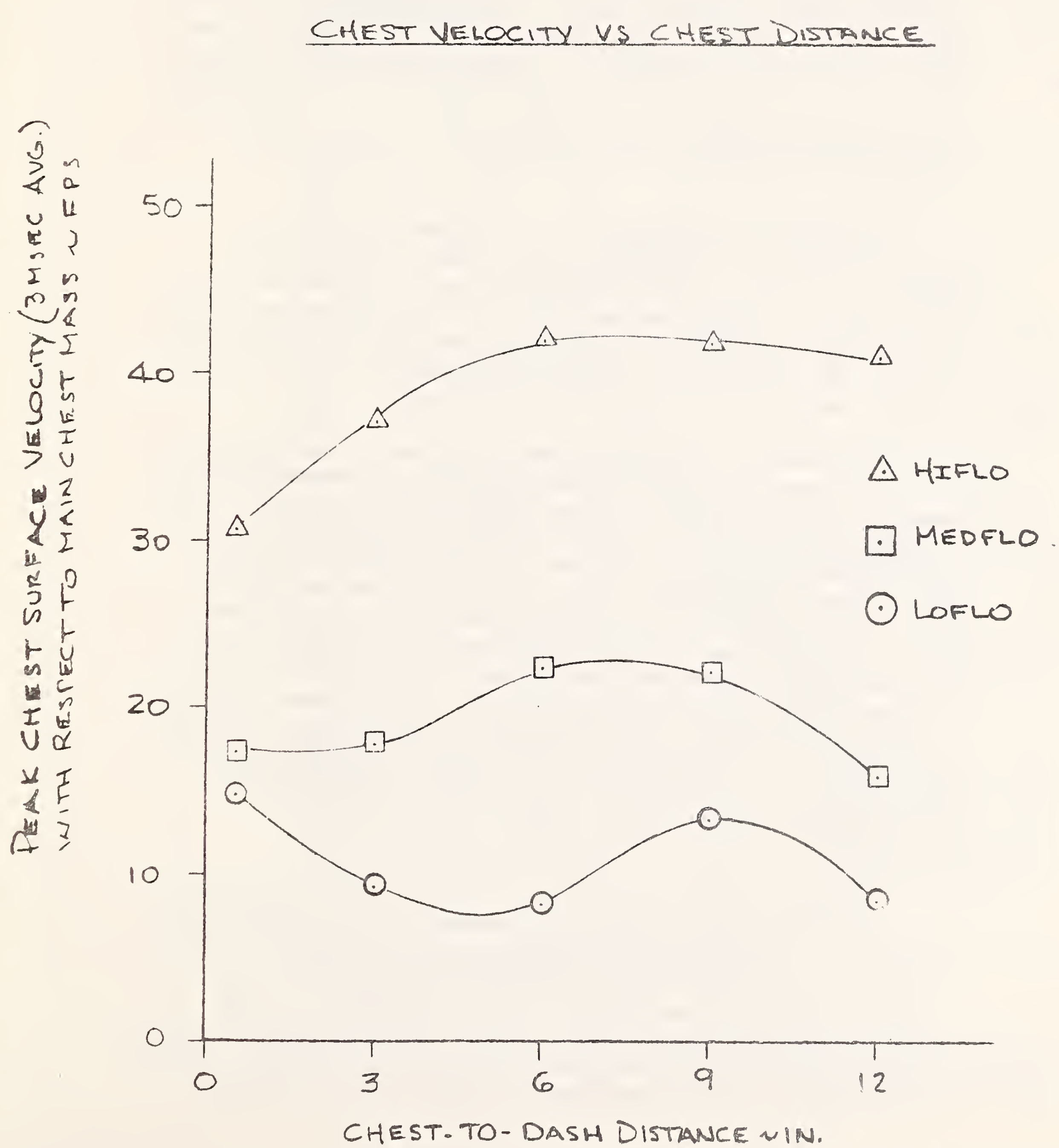
Figure 31.

profile to the HIFLO gas flow profile. This effect is not really new as it was observed in other parts of the study for the 6 inch chest-to-dash spacing used there. What is new is that we have now verified that this effect occurs for all chest-to-dash spacings. Therefore, it may now be concluded that the chest g's during the bagslap phase are a strong function of the initial rate of flowonset into the airbag for all values of the initial chest-to-dash separation distance.

A second piece of information that may be gained from Figure 31 is that, generally speaking, for all three gas flow profiles, the peak bagslap g's increase with increasing chest-to-dash distance up to approximately 9 inches. This increase is due to the increasing velocity of impact of the airbag with the chest as the chest is located farther and farther from the dash. After about 9 inches, however, the combined effects of the slowing bag velocity due to the bag getting ahead of the driving pressure force (as evidenced by low pressure or vacuum readings in testing), and the declining mass of the bag front, tend to slow the rate of increase of chest g's, or even lower them in the case of MEDFLO and LOFLO. Similar maxima have been observed in sled testing with out-of-position child dummies.

A further phenomenon of the effect chest-to-dash distance plays in the overall response of the out-of-position child will now be investigated.

Figure 32 shows a plot of the peak chest surface velocity change averaged over three milliseconds versus the initial distance of separation of the chest from the dash. By "peak chest surface velocity averaged over three milliseconds" it is meant that the absolute peak chest surface velocity with respect to the main chest mass is found and then it is averaged with values of chest surface velocity that occur immediately 1.5 milliseconds before and 1.5 milliseconds immediately after the peak value. This yields an average value for the peak chest surface change velocity over a three millisecond interval. This is not the same as a three millisecond "clip" as this would yield an even lower velocity since only the value at the end points of the interval would be considered. This averaging was done to eliminate high frequency velocity "spikes" that the digital computer can follow but which would most probably not have a physical or biomechanical manifestation in the internal body cavity. The fluidic nature of internal organ supports and their natural frequencies would effectively preclude these velocity



CHEST VELOCITY VS CHEST DISTANCE
PEAK CHEST SURFACE VELOCITY (3 MSEC AVG.)
WITH RESPECT TO MAIN CHEST MASS ~ FPS
50
40
30
20
10
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
HIFLO
MEDFLO
LOFLO

Figure 32.

spikes from being transmitted to these organs. Admittedly however, without detailed biomechanics studies, the three millisecond average is arbitrary at this point and other values can be picked out of the DEPLOY output as additional biomechanical guidance is forthcoming.

From Figure 32 it can again be seen the strong effect the gas flow profile has on the chest surface response during bagslap (recall that all three flow profiles result in the same total amount of gas entering the airbag). The most impulsive flow profile, HIFLO, results in by far the highest chest surface velocity. Correspondingly, as the rate of flow onset is reduced to the MEDFLO profile, the peak chest surface velocity is dramatically reduced until, with the LOFLO profile, the peak velocities are a factor of 3 to 4 lower than for the HIFLO case. Here again, the strong effect gas flow tailoring has on overall chest response is evident.

There is some biomechanical evidence that chest surface velocity change may be a better indicator of injury than the high frequency acceleration fluctuations the chest undergoes as the airbag strikes the chest. If so, it can be seen that the HIFLO type of gas flow profile may not be desirable as a gas flow source due to the high velocities of the chest wall it produces.

Now consider the effect chest-to-dash spacing has on the peak chest surface velocity attained. The mechanism that determines just what the chest surface velocity will be for a given initial chest-to-dash distance is complex with a large number of things happening simultaneously. The airbag itself is growing in diameter while the mass of the rolled up bagfront is decreasing as the deployment process continues. The airbag pressure is oscillating as the pressure alternately pushes and then "pulls" on the airbag. By "pulls" we mean that as the bag front velocity increases, the bag can "get ahead" of the driving pressure resulting in a "stall" period of slower or even negative bag growth. Such periods are evident in experimental tests when the bag pulls a vacuum on the pressure transducer.

Simultaneously with these airbag dynamics, the child is approaching the airbag at a relative rate dependent on the crash pulse and the airbag dynamics. Once the airbag impacts the child's chest, subsequent happenings are a function of numerous factors such as velocity of the airbag relative to the chest, degree of damping exhibited on this velocity by the chest wall and the fluidics of the chest cavity, the instantaneous value of the effective

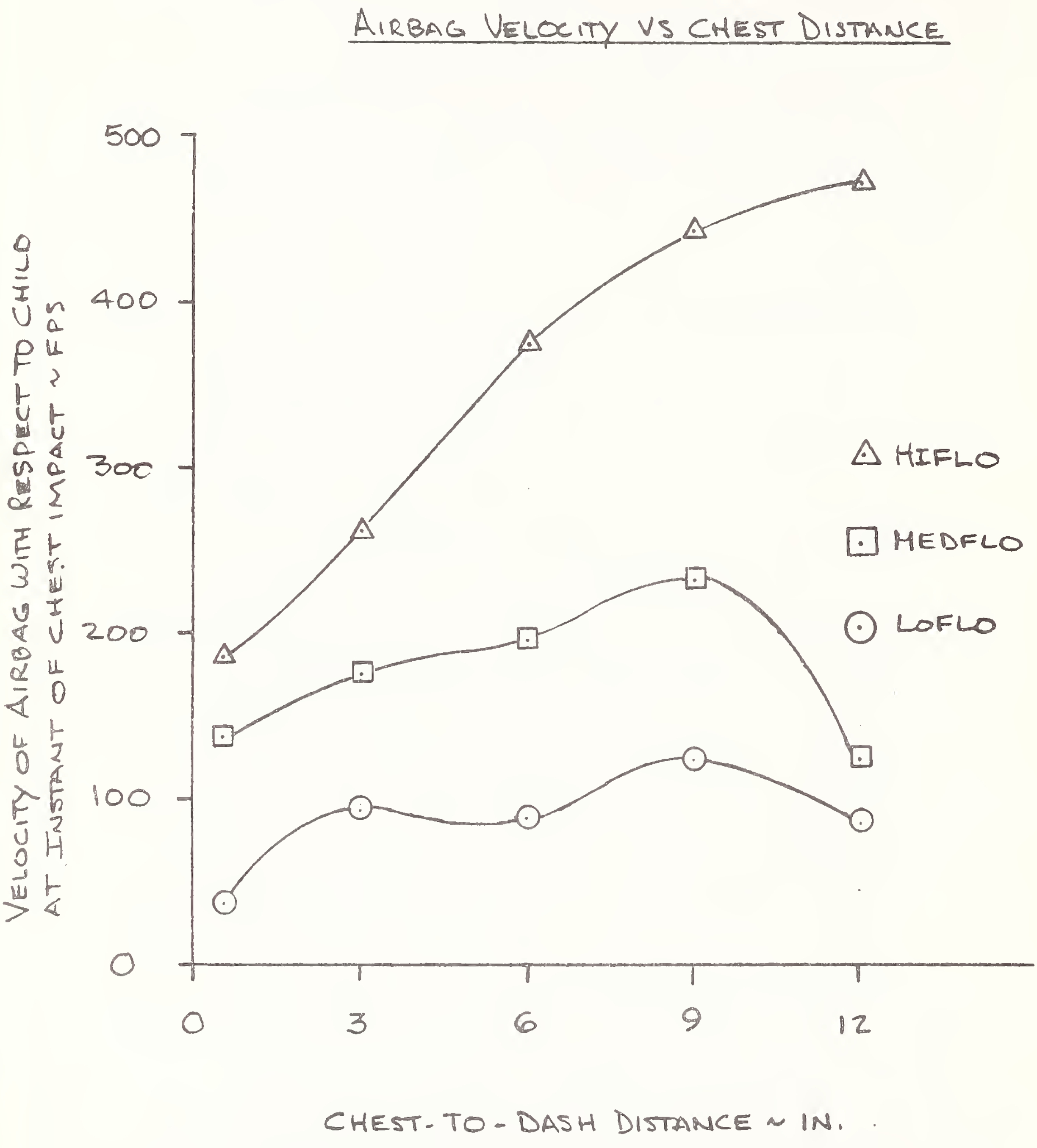
airbag mass, whether the chest surface is moving toward or rebounding away from the approaching airbag at the time subsequent impacts of the chest wall with the airbag occur, etc. All of these parameters are constantly changing so that as what is believed to be a simple change is made, whether it be in a test or computer simulation, such as increasing the distance of the chest from the dash by a few inches, many factors come into play to determine what the net effect will be.

Overall however, even though the mechanism that produces it is complex, the controlling parameter on peak bagslap chest g's seems to be the velocity of the airbag with respect to the chest at the instant of chest contact. Airbag mass effects appear to be of second order.

Looking now at Figure 33 in which the velocity of the airbag with respect to the chest at the instant of the most severe chest impact (several impacts of the bag with the chest usually occur during the bagslap phase; here we are concerned with the particular impact that results in highest chest surface change in velocity) is plotted versus chest-to-dash distance, we see a great degree of similarity to the curve previously presented in Figure 31. We therefore conclude that the peak chest surface g's are a strong function of the velocity of the bag front with respect to the child at the instant of chest impact. This result may seem somewhat intuitive, and to a certain extent it is, however it shows that the bag velocity correlates most strongly with the degree of injury that might be received while the instantaneous value of the unrolling bag mass contributes only secondarily. Previous to this analyis there was some uncertainty among researchers about which of these two factors, bag velocity or bag mass, was the controlling parameter. It now can be said that it is bag velocity that is by far the stronger parameter in influencing potential injury that may be received by the out-of-position child during the airbag deployment process. Further, since bag velocity is determined by the gas flow profile, it can be seen again the very strong effect of gas flow profile on the impact response of the forward position child to the deploying airbag. This again shows the desirability of providing the optimum flow profile for a given impact situation.

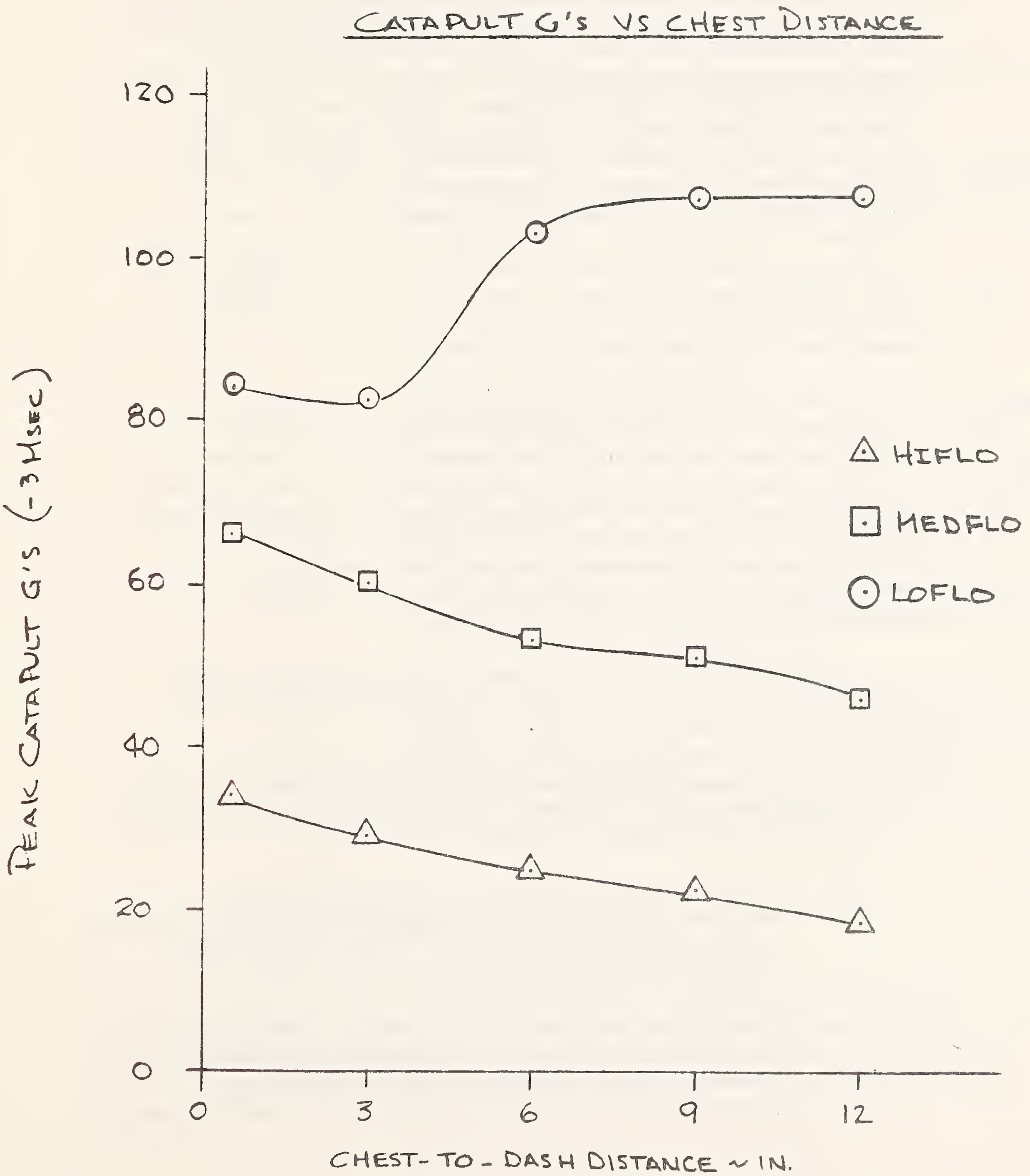
We will now investigate the effects of chest-to-dash distance on the catapult g levels.

In Figure 34 a plot showing the catapult g's that result from various initial separation distances of the chest from the dash was presented. As would be expected,



AIRBAG VELOCITY VS CHEST DISTANCE
VELOCITY OF AIRBAG WITH RESPECT TO CHILD
AT INSTANT OF CHEST IMPACT ~ FPS
500
400
300
200
100
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
HIFLO
MEDFLO
LOFLO

Figure 33.



CATAPULT G'S VS CHEST DISTANCE
PEAK CATAPULT G'S (-3 MSEC)
120
100
80
60
40
20
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
HIFLO
MEDFLO
LOFLO

Figure 34.

the higher flow rate flow profiles, with their greater amount of energy absorbed in the efficient ridedown mode, result in the lowest value for catapult g's as shown in the figure for the HIFLO and MEDFLO gas flow profiles. However, the LOFLO gas flow profile with its slow rate of flow onset allowed the child to impact the dash in all cases except when the chest-to-dash distance is 12 inches or, presumably, higher.

The rather strange shape of the LOFLO curve in Figure 34 is best explained on a point-by-point basis. When the dash separation distance is low, the airbag pressure at the time of maximum catapult g's is also low so that, even though the chest impacts the dash, the pressure forces that add to this impact force are relatively low also. However, as we increase the separation distance to six inches, the peak pressure forces occur almost simultaneously with chest impact resulting in a large increase in chest g's. As we proceed still further, the pressure forces become more and more predominate and the dash impact less and less severe until at 12 inches of initial dash separation, the chest g's are due entirely to the pressure effect and no dash impact occurs.

Looking at HIFLO and MEDFLO there is a general lessening in catapult injury severity as the initial chest-to-dash distance is increased. This is because the maximum airbag penetration becomes less and less as the initial separation distance is increased thereby lessening the "slingshot" effect which produces the catapult g's. This is roughly equivalent to the lower force exerted on the slingshot pellet as the distance of "pullback" is decreased.

The findings from the chest-to-dash distance study with the out-of-position child can now be summarized.

1) The maximum g's during bagslap correlate strongly with the velocity of the bag front with respect to the chest at the time of chest impact for all dash separation distances.

2) The peak chest surface velocity change is highest for the impulsive type of gas flow profiles such as HIFLO and lower for the less impulsive MEDFLO and HIFLO gas flow profiles.

3) The LOFLO gas flow profile causes catapult g's which are too high over the entire range of chest-to-dash spacings investigated. We therefore do not consider the LOFLO type of

profile as adequate as a single level gas generation system unless the severe catapult g's are mitigated through bag tethering, dual airbag design for optimum deployment geometry, or some other similar technique.

4) In general the velocity of the bag front and, therefore, chest impact severity during <u>bagslap</u>, increases with increasing distance of the initial chest location with respect to the dash. This effect occurs up to the point in time at which the bag velocity begins to decrease either due to flow profile changes or due to one of the other complex effects mentioned in the foregoing becoming predominant. For this study with the parameters assumed, this reduction in velocity appeared to occur for dash separation distances greater than approximately 9 inches.

5) An opposite effect to that noted in (4) above occurs during the catapult phase however. As discussed in the foregoing, the "slingshot" effect which is the largest contributor to catapult g levels generally lessens as the chest is located farther and farther from the dash. Thus, for a case where the chest is located very close to the dash, one would, in general, expect relatively low initial bagslap g's followed later by higher catapult g's. Conversely, for an initial dash separation distance that is relatively high, one would, in general, expect relatively high initial bagslap g's followed by relatively lower catapult g's.

6) Overall, the MEDFLO type of gas flow profile appears the most promising for a a single level system design which will protect both the normally seated passengers as well as the out-of-position child during the entire impact event from bagslap through catapult.

5.0 SYSTEMS ANALYSIS APPROACH TO AIRBAG DESIGN

As stated above, the MEDFLO type of gas flow profile appears, for any single level generator, to have the most promise for meeting all the criteria specified for a viable airbag design. It alone as a single level gas generation system, appears to provide the combination of protection for the normally seated passengers as well as the

out-of-position child from the bagslap through the catapult phases of airbag deployment. Further, through what was learned in this study in Section 4.3, the restraint system designer may further increase the probability of success of the total design by using an airbag with the highest length-to-diameter as is practical. And, finally, some slight additional benefit will be realized for certain flow profiles by decreasing the airbag fabric weight.

The system studied in the previous sections will now be modified to take advantage of all these findings and the results of this "improvement" will be compared with what was realized in the study results presented in the preceding sections for the same gas flow profile.

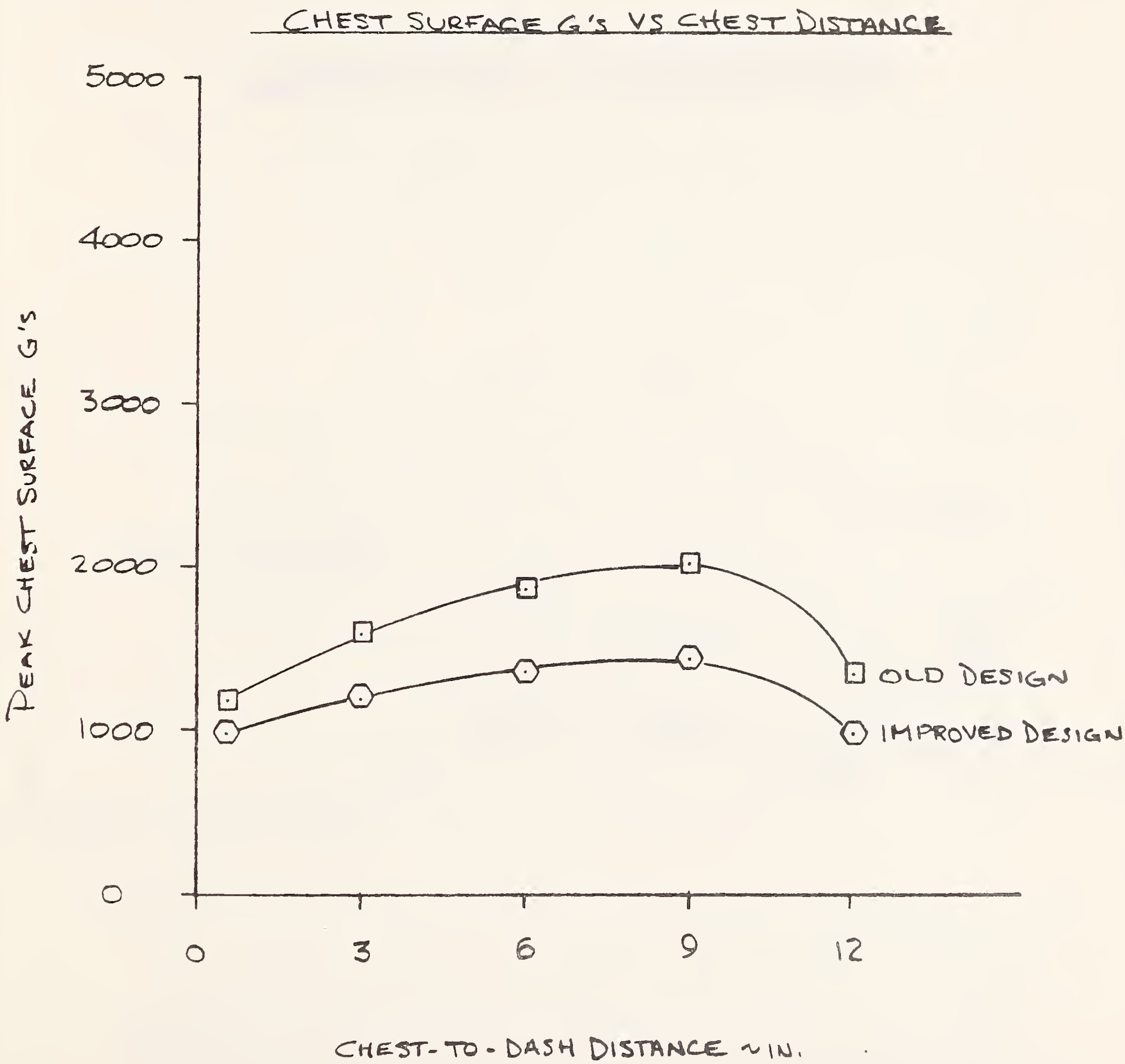
The Table 3 summarizes the two systems. Recall that the systems described below have both been previously shown to provide satisfactory performance with the normally seated adult at 30 mph impact velocity before being considered as candidates for the forward positioned child study.

Table 3
System Improvements

Parameter	Section 4.6 System	New "Improved" System
Airbag L/D:	2.04	3.0
Airbag Fabric Wgt:	8.4 oz./sq.yd.	5.0 oz./sq.yd.
Gas Flow Profile:	MEDFLO	MEDFLO

In both cases the airbag volume is ten cubic feet with a total of 312 grams of gas flowing into the airbag.

Figures 35 through 37 show the results of using the findings of this study to "improve" the design investigated in the previous section (Section 4.6). As may be seen by studying the figures, in each case the peak chest surface g's, the peak chest surface velocity, and the peak catapult g's were all reduced by making those changes to the design deemed appropriate by the things discovered in the analyses presented in this report. By using this knowledge, we are able to improve the design where to the point the system performance results in the chest criteria being satisfied for both the normally seated passenger as well as for the out-of-position child for the entire deployment sequence and for all chest-to-dash initial separation distances. Through further modification, by way of additional computer study with systems of interest we are confident the design could be further improved.



CHEST SURFACE G'S VS CHEST DISTANCE
5000
4000
3000
2000
1000
0
PEAK CHEST SURFACE G'S
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
OLD DESIGN
IMPROVED DESIGN

Figure 35.

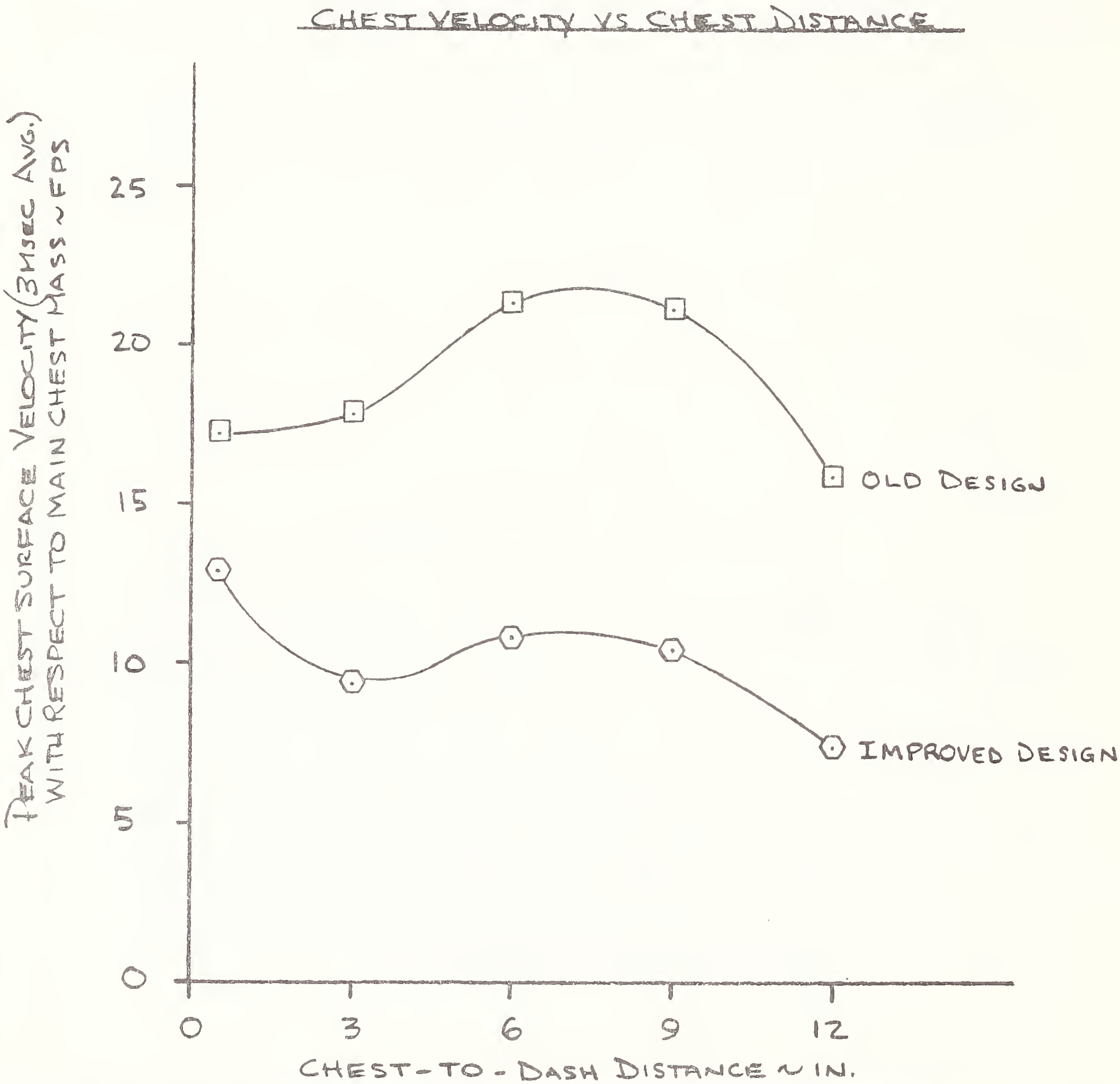
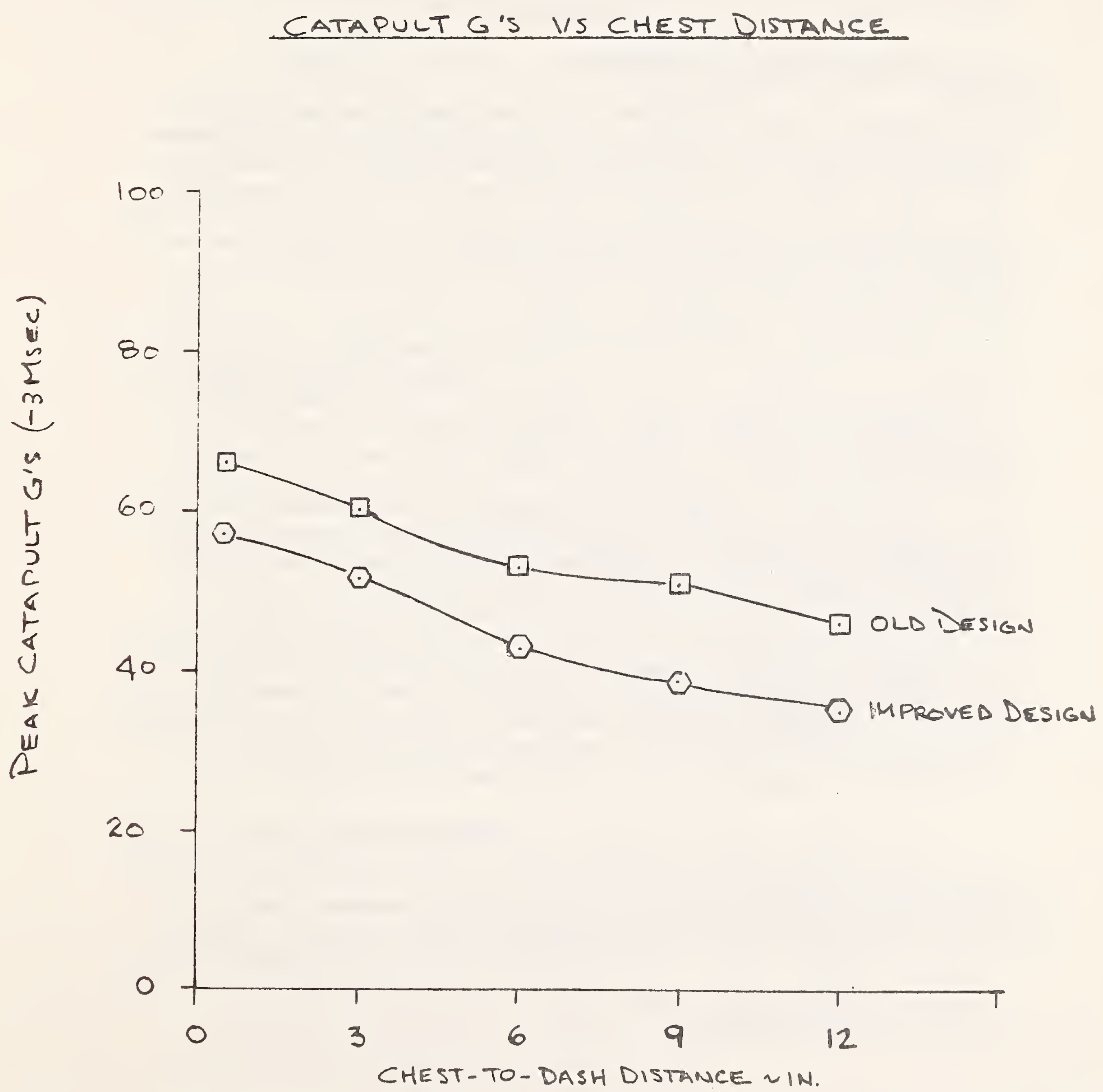

CHEST VELOCITY VS CHEST DISTANCE
PEAK CHEST SURFACE VELOCITY (3 MSEC AVG.) WITH RESPECT TO MAIN CHEST MASS ~ FPS
25
20
15
10
5
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
OLD DESIGN
IMPROVED DESIGN

Figure 36.



CATAPULT G'S VS CHEST DISTANCE
PEAK CATAPULT G'S (-3 Msec)
100
80
60
40
20
0
0
3
6
9
12
CHEST-TO-DASH DISTANCE ~ IN.
OLD DESIGN
IMPROVED DESIGN

Figure 37.

6.0 CONCLUSIONS

6.1 Mass Flow Tailoring

Of all the parameters and mitigation techniques studied, inflator mass flow tailoring has the greatest and most pervasive effect on the responses of the out-of-position child. The rate of onset of the mass flow of gas out of the inflator has a strong and positive correlation with bagslap chest g's. Also, the inflator gas flow profile has a strong interrelationship with most of the other parameters studied as detailed below.

6.2 Multiple Level Inflation Sequences

Multiple level inflation can substantially reduce bagslap exposures for the out-of-position child while maintaining optimum system performance for the normally seated adult. General Motors used crash sensing to initiate deployment of a staged two-level inflator system in their 1973-76 air cushion cars and Daimler Benz reports they will use a dual level sensing and inflation system in their production air cushion cars.

Two types of sensing are available to initiate deployment in a dual level system. The first is, as discussed above, judiciously placed crash sensors set to low and high level velocity changes to initiate the different levels. The second is occupant size or weight sensors in the seat or elsewhere which tell the system to fire the high level if there is a heavy occupant in the seat.

The predictive sensing of occupant size or proximity, or both, has benefits because, in a crash, the high level would go at the first possible moment a deployment signal is received (providing maximum ridedown potential) if a large occupant is in the seat.

In using crash sensing alone to initiate a dual level system, the high level delta V sensor will fire at some time lag after the low delta V sensor (unless it is positioned further forward in the car). It remains to be seen in further investigations into sensing scenarios for the dual level inflation system, if such a delay has unacceptable consequences for the normally seated adult.

For either sensing scenerio, added reliability concerns can be largely offset by having the low level system always go off in any deployment demand situation, but only have the high level booster go off if a positive indicative signal is received by the diagnostics of either a heavy occupant in the seat, or a severe crash, or both. Also, if the low level system meets FMVSS No. 208 for the passenger at 30 mph, reliability equal to any single level system will be assured.

6.3 Bag Fabric Mass

The effect of bag fabric mass on chest bagslap g's is highly interdependent with the mass flow profile out of the inflator. For slow onset rate inflators, the forward positioned child's bagslap g's are nearly independent of fabric weight over a reasonable range of fabric weights. However, for the more impulsive type inflators such as the stored gas systems or the ganged driver units, fabric weights correlate strongly and positively with the bagslap g's for the child.

6.4 Aspiration and Pressure Dump Features

The analysis based on the DEPLOY computer model does not predict much benefit, if any, in reducing bagslap from aspiration or pressure dump features. The reason for this is that the bagslap event is very short in duration, typically 1 to 3 milliseconds, and is over before any alternate deployment mode, based on pressure feedback or flow redirection, can occur.

Aspiration has some secondary benefits like reducing catapult g's for the forward positioned child, but these do not seem to be superior to what can be obtained with judicious flow tailoring of conventional inflators or multiple level system design, or both.

6.5 Chest-to-Dash Spacing

In the 0 to 12 inch range, chest-to-dash spacing is a significant variable in determining the response of the forward positioned child's chest and is strongly interrelated to the rate of onset of the mass flow from the inflator. A peaking in the chest surface bagslap g's is apparent around 9 inches for the low to medium flows while for the high flow rates, chest g's continue to increase with an increase in chest spacing but the rate of increase is much slower above 8 inches. The much higher bag front velocities associated with high flow profiles directly relate to higher bagslap g's at all chest-to-dash spacings but are much more pronounced for the HIFLO Case at spacings above 6 inches. During the catapult phase a nearly opposite effect occurs. As the chest is located further from the dash, the waterwing forces are lower, resulting in lower catapult g's.

6.6 Air Bag Shape and Volume

The effect of airbag shape on the forward positioned child's chest is that the chest surface g's and resultant velocity changes decrease as the length-to-diameter (L/D) ratio increases up to the point where the chest goes through the bag and contacts the dash.

As the L/D ratio is increased, the system becomes less dependent on a specific inflator flow profile characteristic to give acceptable bagslap and catapult g's.

The bag shape has fundamental influences on the bagslap and catapult phases; on bagslap because, for lower L/D ratios, more bag fabric will contact the out-of-position child's chest and will consequently increase bagslap; on catapult because, for lower L/D ratios, the forward positioned child will be subjected to larger waterwing and pressure stroke forces.

The air bag volume alone (normalized for inflation gas) has a minimal effect on bagslap or catapult; however, air bag volume can be the result of other interrelated bag design parameters which can strongly affect either bagslap or catapult, or both.

6.7 Systems Analysis Approach

As stated in the introductory remarks, the ultimate goal of this study was a systems approach to determining the effects on the out-of-position child of the many independent and dependent variables in air bag design and analysis. This implies, and it should be definitely restated here, that the combined effects of the variables and parameters will many times be just as important, if not more important, than the isolated effects of a single variable. It has been confirmed in this study that the inopportune or uninformed adjustment of one parameter in the wrong direction can more than outweigh the adjustment of another parameter in a beneficial direction, with a net loss in benefit.

Some of the more significant interrelationships discovered in this study were those between flow tailoring and the following: bag fabric weight, chest-to-dash spacing, and air bag shape. Other relationships exist as detailed in the report. Others undoubtedly are yet to be discovered with the additional use and expansion of the model. It should be emphasized here that probably the most significant finding of this study is the basic and unavoidable requirement that in order to pursue a systems analysis approach to air bag design and analysis (to "know where one is on the curve" while trying to optimize the many design parameters) the use of advanced modeling and computational techniques using high capacity digital computers, backed by extensive developmental experience in the laboratory, is essential.

APPENDIX A

LISTING OF DEPLOY COMPUTER PROGRAM

DEPLOY 03/13/80

```
100 REM              =============DEPLOY==============
110 REM
120 REM
130 REM THIS PROGRAM IS BASED UPON A PREVIOUS PROGRAM KNOWN AS "BAGSLAP"
140 REM AND IS EXPANDED AND IMPROVED OVER THE ORIGINAL VERSION. ANOTHER CHEST
150 REM MASS HAS BEEN ADDED, THE BAG DEPLOYMENT ALGORITHM IMPROVED,
160 REM AND ADDITIONAL OUTPUT PROVIDED.
170 REM
180 REM THE PROGRAM COMPUTES THE INTERACTION OF A VEHICLE PASSENGER
190 REM WITH A DEPLOYING AIRBAG IN A CRASH OR NON-CRASH SITUATION.
200 REM THE USER SPECIFIES CERTAIN VARIABLES SUCH AS BAG SHAPE AND VOLUME,
210 REM BAG WEIGHT, VENT AREA, VENT ACTUATION PRESSURE,PASENGER WEIGHT,
220 REM WEIGHT OF CHEST SURFACE, IMPACT VELOCITY, CHEST WIDTH, GAS FLOW
230 REM PARAMETERS,CHEST SURFACE AND CHEST OVERALL FORCE-DISPLACEMENT PARA-
240 REM METERS, CRASH PULSE AND A FEW OTHER PARAMETERS.
250 REM
260 REM THE PROGRAM THEN COMPUTES THE DYNAMICS OF THE INTERACTION OF THE
270 REM DEPLOYING AIRBAG AND THE PASSENGER. TYPICAL OUTPUT WOULD BE THE
280 REM ACCELERATIONS OF THE PASSENGER, THE AIRBAG AND BOTH CHEST MASSES; THE
290 REM VELOCITY OF THE VEHICLE, PASSENGER, AIRBAG, AND THE CHEST MASSES; THE
300 REM DISPLACEMENT OF THE VEHICLE, AIRBAG AND THE CHEST MASSES; AS WELL
310 REM AS THE OTHER PARAMETERS OF INTEREST SUCH AS CHEST PENETRATION OF THE
320 REM AIRBAG, PRESSURE IN THE BAG, VOLUME OF THE BAG, MASS RATE OF FLOW OF
330 REM GAS EXITING THE BAG, AND THE CHEST FORCES.
340 REM
350 REM
360 REM                PROGRAM AUTHOR: MICHAEL FITZPATRICK
370 REM                COMPANY:        FITZPARICK ENGINEERING
380 REM                ADDRESS:        ROUTE 5, BOX 495A
390 REM                                WARSAW, IN  46580
400 REM                TELEPHONE:      (219) 267-4437
410 REM
420 REM
430 PRINT "ENTER AIR BAG DEPLOYMENT TIME T9=?"
440 INPUT T9
450 PRINT "IF YOU WANT ALL THE OUTPUT PRINTED, TYPE YES; IF YOU WANT ONLY";
460 PRINT "THE MAIN PARAMETERS PRINTED, TYPE NO."
470 INPUT P$
480 READ 00,I1,02,12,03,I3,04,I4,05,I5
490 READ P0,A0,L1,B1
500 READ A5,P2,N1,N2,N3
510 READ C1,C2,T5
520 READ P0,T0,P9
530 READ W0,W6,S0,B0
540 READ B2,W2,B3,W3,B4,W4,B5,W5
550 READ C6,P9
560 READ N6,X9,L9,D9,D4
570 READ F1,U1,F2,U2,F3,U3,F4,U4
580 READ M6,R1,V1,R2,V2,R3,V3,R4,V4
590 PRINT " "
```

```
DEPLOY        03/13/80


600 PRINT " "
610 PRINT TAB(12);"DYNAMICS OF IMPACT WITH A DEPLOYING AIRBAG"
620 PRINT TAB(12);"=========================================="
630 PRINT
640 PRINT TAB(8);"BAG DIAM=";2*R0;"INCHES BY";2*(A0+R0);"INS LG, BAG WGT=";M6;"O
Z PER SQ YD"
650 PRINT TAB(8);"VENT AREA=";A5;"SQ IN";TAB(35);"OPENED AT";P2;"PSIG"
660 PRINT TAB(8);"INITIAL PRESS=";P0;"PSIG AT ";T0-460;"DEG F, DASH PAD=";P9;"G/
IN"
670 PRINT TAB(8);"PASS. WGT.=";W0;"LBS,  CHEST SUR. WGT.=";W6;"LBS, VEL.=";S0;"F
PS"
680 PRINT TAB(8);"PASS. EFF. HGT.=";L1;"IN., CHEST WIDTH=";2*B0;"IN"
690 PRINT TAB(8);"INIT. DIST. FROM DASH=";C6;"IN., MANIFOLD SOCK, L=";L9;"IN., D
IA=";X9;"IN."
700 PRINT TAB(8);"FACTOR ON PASS. WGT. DURING BAGSLAP=";N6;", VENT COEFF.=";B1
710 PRINT TAB(8);"CHEST DAMPING COEFF.: SURFACE=";D9;", MAIN=";D4
720 PRINT TAB(8);"GAS FLOW (LB/SEC-TIME)=";Q0;I1;Q2;I2;Q3;I3;Q4;I4
730 PRINT TAB(31);Q5;I5
740 PRINT TAB(8);"CHEST SURFACE (LB-DISP)=";F1;U1;F2;U2;F3;U3;F4;U4
750 PRINT TAB(8);"OVERALL CHEST (LB-DISP)=";R1;V1;R2;V2;R3;V3;R4;V4
760 PRINT TAB(8);"CRASH PULSE (G'S-TIME)=";B2;W2;B3;W3;B4;W4;B5;W5
770 PRINT
780 PRINT
790 PRINT TAB(3);"TIME";TAB(9);"G G/S";TAB(16);"V FPS";TAB(23);"VV FPS";
800 PRINT TAB(31);"X IN";TAB(40);"X1 IN";TAB(48);"P PSIG";
810 PRINT TAB(56);"VOL CI";TAB(63);"Q #/SEC";TAB(73);"G6"
820 PRINT TAB(3);"====";TAB(9);"=====";TAB(16);"=====";TAB(23);"======";
830 PRINT TAB(31);"====";TAB(40);"=====";TAB(48);"======";
840 PRINT TAB(56);"======";TAB(63);"=======";TAB(73);"=="
850 DIM T(700),X(700),E(700),D(700),C(700),Y(700),S(700),Z(700),R(700)
860 DIM F(700),H(700)
870 FILES BAGOUT
880 SCRATCH #1
890 R8=(2/(N1+1))^(N1/(N1-1))
900 M2=C2*SQR(R9^(2/N1)-R8^((N1+1)/N1))
910 L2=L1
920 I=X2=U=G=T6=G6=0
930 X3=X9=X6=G3=G8=0.
940 Q1=0.
950 N4=N2
960 L4=L0
970 G1=J1=Q1=H2=0.
980 P=P0+14.4
990 P5=P
1000 P1=P0
1010 T=530
1020 R=K=0.
1030 A6=A5
1040 S3=S8=S2=S1=S6=S0*12.
1050 X=2*R0-C6
1060 D3=D8=0.
1070 L6=L1*(W6/W0)**.333
1080 V=3.141*(D3**3/3.+B0*D3*D3+D3**2*(A0+R0-B0-D8/2.))/2.+3.141*X9**2*L9/4.
1090 M0=4.*3.14*R0*M6*(A0+R0)/20736.
```

DEPLOY 03/13/80

```
1100 W=(P1+14.4)*V/(R4*530.)
1110 IF T6<=M2 THEN 1170
1120 IF T6<=M3 THEN 1190
1130 IF T6<=M4 THEN 1210
1140 IF T6<=M5 THEN 1230
1150 G1=0.
1160 GO TO 1240
1170 G1=-T6*B2/M2
1180 GO TO 1240
1190 G1=-B2-(T6-M2)*(B3-B2)/(M3-M2)
1200 GO TO 1240
1210 G1=-B3-(T6-M3)*(B4-B3)/(M4-M3)
1220 GO TO 1240
1230 G1=-B4-(T6-M4)*(B5-B4)/(M5-M4)
1240 IF I=0 THEN 1260
1250 X1=X1+S1*T5+193.2*G1*T5**2
1260 S1=S1+386.4*G1*T5
1270 S9=S1/12
1280 IF I=0 THEN 1320
1290 X3=X3+S3*T5+193.2*G3*T5**2
1300 S3=S3+386.4*G3*T5
1310 X6=X6+S6*T5+193.2*G6*T5**2
1320 S6=S6+386.4*G6*T5
1330 IF I=0 THEN 1350
1340 X2=X2+S2*T5+193.2*G*T5**2
1350 S2=S2+386.4*G*T5
1360 S0=S2/12
1370 X=X2-X1-(C6-2*R0)
1380 D6=X6-(X3+C6)
1390 IF D6<=U1 THEN 1430
1400 IF D6<=U2 THEN 1450
1410 IF D6<=U3 THEN 1470
1420 IF D6<=U4 THEN 1490
1425 IF D6>U4 THEN 1495
1430 F=0
1440 GO TO 1500
1450 F=F1+(F2-F1)*(D6-U1)/(U2-U1)
1460 GO TO 1500
1470 F=F2+(F3-F2)*(D6-U2)/(U3-U2)
1480 GO TO 1500
1490 F=F3+(F4-F3)*(D6-U3)/(U4-U3)
1493 GO TO 1500
1495 F=F4
1500 IF F>0 THEN 1520
1510 GO TO 1550
1520 F=F+(S6-S3)*D4
1530 IF F>0 THEN 1550
1540 F=0
1550 G6=-(F-R)/M5
1560 D2=X2-X6
```

[illegible]

```
1570 IF D2<=V1 THEN 1610
1580 IF D2<=V2 THEN 1630
1590 IF D2<=V3 THEN 1650
1600 IF D2<=V4 THEN 1670
1605 IF D2>V4 THEN 1675
1610 R=0.
1620 GO TO 1680
1630 R=R1+(R2-R1)*(D2-V1)/(V2-V1)
1640 GO TO 1680
1650 R=R2+(R3-R2)*(D2-V2)/(V3-V2)
1660 GO TO 1680
1670 R=R3+(R4-R3)*(D2-V3)/(V4-V3)
1673 GO TO 1680
1675 R=R4
1680 R=R+(L2-L6)*D4
1690 IF R>0 THEN 1710
1700 R=0
1710 G=-R/(N6*(W0-W6))
1720 IF A2>L1 THEN 1750
1730 L2=A2
1740 GO TO 1760
1750 L2=L1
1760 IF P1>0 THEN 1780
1770 GO TO 1840
1780 IF R>0 THEN 1800
1790 GO TO 1840
1800 G=G-P1*L2*D8*H1/((H0+R0-B0)*2.*N6*(W0-W6))
1810 IF L2>L6 THEN 1830
1820 GO TO 1840
1830 G=G-2.*B0*P1*(L2-L6)/(N6*(W0-W6))
1840 IF I=0 THEN 1870
1850 X8=X8+S8*T5+193.2*G8*T5**2.
1860 S8=S8+386.4*G8*T5
1870 D3=X1-X3
1880 D8=X1-X8
1890 H1=D8-D3
1900 IF H1>2.*R0 THEN 1920
1910 GO TO 1930
1920 H1=2.*R0
1930 IF H1>R0+H0-B0 THEN 1950
1940 GO TO 1960
1950 H1=R0+H0-B0
1960 IF H1>0. THEN 2000
1970 H1=0.
1980 H2=0.
1990 GO TO 2040
2000 IF H1<D8/2. THEN 2030
2010 H2=D8
2020 GO TO 2040
2030 H2=2.*SQR(H1*(D8-H1))
```

T-PLOT   06/13/80

```
2040 V=3.141*(D8**3/3.+B0*D3*D8+D8**2*(A0+R0-B0-D8/2.))/2.+3.141*Z4**2*L9/4.
2050 IF T6<=I1 THEN 2100
2060 IF T6<=I2 THEN 2120
2070 IF T6<=I3 THEN 2140
2080 IF T6<=I4 THEN 2160
2090 IF T6<=I5 THEN 2180
2100 Q1=0.
2110 GO TO 2190
2120 Q1=Q0+(Q2-Q0)*(T6-I1)/(I2-I1)
2130 GO TO 2190
2140 Q1=Q2+(Q3-Q2)*(T6-I2)/(I3-I2)
2150 GO TO 2190
2160 Q1=Q3+(Q4-Q3)*(T6-I3)/(I4-I3)
2170 GO TO 2190
2180 Q1=Q4+(Q5-Q4)*(T6-I4)/(I5-I4)
2190 W1=W+Q1*T5
2200 IF T6<I1 THEN 2270
2210 T7=(W*T+Q1*T5*T0)/W1
2220 P7=(R9*T7*W1)/V0
2230 P8=((R9*T7*W1/V)**N4)/(P7**(N4-1))
2240 T8=T7*(P8/P7)**((N4-1)/N4)
2250 P1=P8-14.4
2260 GO TO 2290
2270 P=P0+14.4
2280 GO TO 2530
2290 IF T6<T9 THEN 2440
2300 IF P1<P2 THEN 2440
2310 P2=0.
2320 R7=14.4/P8
2330 IF R7<R8 THEN 2360
2340 M1=C1*SQR(R7^(2/N1)-R7^((N1+1)/N1))
2350 GO TO 2370
2360 M1=M2
2370 A5=A6+B1*P1**2
2380 IF A5<A6 THEN 2400
2390 GO TO 2410
2400 A5=A6
2410 U=SQR((772*N1)/(N1-1))*A5*P8*M1/SQR(R9*T8)
2420 W=W1-U*15
2430 GO TO 2460
2440 W=W1
2450 U=0
2460 P=P8*(W/W1)**N1
2470 T=T8*(W/W1)**(N1-1)
2480 R6=P8/P5
2490 IF R6<1.0001 THEN 2520
2500 N4=N2
2510 GO TO 2530
2520 N4=N3
2530 P1=P-14.4
```

DEPLOY   08/13/80

```
2540 M3=M0*B0*(1-D8/(2.*R0))/(A0+R0)
2550 M3=M3+(M0-M3)*D8*B0/(2.*3.141*(R0*A0+R0**2))
2560 M8=(A0+R0-B0)*M0*(1-D8/(2.*R0))/(A0+R0)
2570 M8=M8+(M0-M8)*D8*(R0+A0-B0)/(2.*3.141*(R0*A0+R0**2))
2580 IF X>=2.*R0 THEN 2950
2590 IF D8>=2.*R0 THEN 2890
2600 IF D8>1. THEN 2680
2610 IF P1>0. THEN 2650
2620 G8=G3=G1
2630 S8=S3=S1
2640 GO TO 3060
2650 G3=(F-X9*L9*P1)/M0
2660 G8=-P1*X9*L9/M0
2670 GO TO 3060
2680 IF S2>S3 THEN 2740
2690 IF F>0 THEN 2740
2700 S3=S6=S2
2710 IF P1>0.0 THEN 2850
2720 G3=G6=G
2730 GO TO 2865
2740 IF P1>0. THEN 2830
2750 G8=G1
2760 S8=S1
2770 IF F>0. THEN 2810
2780 G3=G1
2790 S3=S1
2800 GO TO 3060
2810 G3=F/M3
2820 GO TO 3060
2830 G3=(F-2.*D8*B0*P1)/M3
2840 GO TO 2865
2850 G3=G6=G=-2*P1*L2*(B0/(M3+W0)+D8*A1/((A0+R0-B0)*4.*(M8+W0)))
2865 IF A0-B0>0. THEN 2875
2870 G8=-P1*(2.*D8*(A0-B0)+3.141*D8**2/4.)/M8
2872 GO TO 2880
2875 G8=-P1*3.141*D8**2/(4.*M8)
2880 GO TO 3060
2890 D8=2.*R0
2900 IF P1>0. THEN 2930
2910 G=0.
2920 GO TO 2990
2930 G=-2.*P1*L2*(B0/(M3+W0)+D8*A1/((A0+R0-B0)*4.*(M8+W0)))
2940 GO TO 2990
2950 IF P1>0. THEN 2980
2960 G=-P9*(X-2.*R0)
2970 GO TO 2990
2980 G=-P9*(X-2.*R0)-2.*P1*L2*(B0/(M3+W0)+D8*A1/((A0+R0-B0)*4.*(M8+W0)))
2990 G3=G6=G
3000 S3=S6=S2
3010 IF D8>=2.*R0 THEN 3030
```

```
3020 GO TO 2365
3030 G6=G1
3040 S8=S1
3050 D8=2.*R0
3060 IF X<0. THEN 3500
3070 IF T6<I1 THEN 3130
3080 IF S2=S3 THEN 3110
3090 U=5
3100 GO TO 3140
3110 X6=X2
3120 X3=X6-C6
3130 U=25
3140 IF INT(I/U)=I/U THEN 3170
3150 GO TO 3180
3160:   .#### ######.## ####.##   ###.####   ###.####   ###.#### ####.####   ######   ###.####   ####.#
# #####.#
3170 PRINT USING 3160,T6,G,S0,S9,X,X1,P1,V,Q,G6
3180 V0=V
3190:   .#### #######.   #####.   ###.###    ####.###   ###.###   #######.   ####.###   ###.###   ######.
3200 X(I)=X
3210 E(I)=X5
3220 D(I)=X3
3230 C(I)=X2
3240 Y(I)=S6/12.
3250 S(I)=S3/12.
3260 Z(I)=D8
3270 R(I)=R
3280 F(I)=F
3290 H(I)=G3
3300 T(I)=T5*(I+1)
3310 IF INT(I/U)=I/U THEN 3330
3320 GO TO 3350
3330 WRITE #1 USING 3190,T(I),H(I),S(I),D(I),Y(I),E(I),F(I),Z(I),C(I),R(I)
3340 K=K+1
3350 I=I+1
3360 T6=T5*I
3370 IF I>650 THEN 3510
3380 GO TO 1110
3390 DATA 0.,.012,15.7,.052,4.28,.112,0.,.147,0.,.16
3400 DATA 13.,13.559,18.,0.
3410 DATA 0.,.5,1.4,1.4,1.4
3420 DATA .7,.7,.0002
3430 DATA 0.,1160.,660.
3440 DATA 33.,1.,44.,3.375
3450 DATA 10.,.012,19.,.048,16.,.091,0.,.117
3460 DATA 6.,25.
3470 DATA 0.5,5.,53.118,0.,2.5
3480 DATA 0.,0.,1600.,1.,3200.,2.,16000.,10.
3490 DATA 8.4,0.,0.,20.,1.,145.,2.,5000.,5.
3500 PRINT TAB(4);"PASSENGER REBOUND OUT OF BAG."
3510 IF P$="NO" THEN 3690
```

DEPLOY 03/13/80

```
3520 PRINT
3530 PRINT
3540 PRINT TAB(3);"TIME";TAB(9);"B G'S";TAB(16);"BV FPS";TAB(23);"BD IN";
3550 PRINT TAB(31);"CSV FPS";TAB(40);"CSD IN";TAB(48);"CSF LB";
3560 PRINT TAB(56);"D8 IN";TAB(63);"PD IN";TAB(70);"PF LB"
3570 J=K-1
3580 RESTORE #1
3590 FOR K=0 TO J
3600 READ #1,T(K),H(K),S(K),D(K),Y(K),E(K),F(K),Z(K),C(K),R(K)
3610 NEXT K
3620 SCRATCH #1
3630 PRINT TAB(3);"====";TAB(9);"=====";TAB(16);"======";TAB(23);"======";
3640 PRINT TAB(31);"=======";TAB(40);"======";TAB(48);"======";
3650 PRINT TAB(56);"======";TAB(63);"======";TAB(71);"===="
3660 FOR K=0 TO J
3670 PRINT USING 3190,T(K),H(K),S(K),D(K),Y(K),E(K),F(K),Z(K),C(K),R(K)
3680 NEXT K
3690 END
```

APPENDIX B

SAMPLE DEPLOY RUN

SIMULATION OF SLED RUN 1637

Special Note

Because of a setback of the inflator and dash from the undeployed bagfront of 2 inches in sled run no. 1637, certain changes were made to the DEPLOY program just for this computer run to accomodate this. Thus three statements were changed from what they are listed as in Appendix A to what is listed below for this run. The added part is underlined.

```
2580 IF X 2.*R0+2. THEN 2950

2960 G=-P9*(X-2.*R0-2.)

2980 G=-P9*(X-2.*R0-2.)-P1*12(B0/(M3+W0)+D8*A1/(4.*(A0+R0-B0)*(M8+W0))
```

CSP163T 15:57EST 02/23/80

ENTER AIR BAG DEPLOYMENT TIME T9=,
? .07
IF YOU WANT ALL THE OUTPUT PRINTED, TYPE YES; IF YOU WANT ONLY
THE MAIN PARAMETERS PRINTED, TYPE NO.
? YES

DYNAMICS OF IMPACT WITH A DEPLOYING AIRBAG
===

BAG DIAM= 20 INCHES BY 24 INS LG, BAG WGT= 10 OZ PER SQ YD
VENT AREA= 35 SQ IN OPENED AT 0.5 PSIG
INITIAL PRESS= 0 PSIG AT 700 DEG F, DASH PAD= 25 G/IN
PASS. WGT.= 33 LBS, CHEST SUR. WGT.= 1 LBS, VEL.= 17 FPS
PASS. EFF. HGT.= 12.4 IN., CHEST WIDTH= 7 IN
INIT. DIST. FROM DASH= 3 IN., MANIFOLD SOCK, L= 14 IN., DIA= 4 IN.
FACTOR ON PASS. WGT. DURING BAGSLAP= 0.5 , VENT COEFF.= 0
CHEST DAMPING COEFF.: SURFACE= 0 , MAIN= 2.5
GAS FLOW (LB/SEC-TIME)= 0 0.051 6 0.067 7 0.097 0 0.151
0 0.16
CHEST SURFACE (LB-DISP)= 0 0 400 1 800 2 4000 10
OVERALL CHEST (LB-DISP)= 0 0 70 1 200 1.33 11500 6.33
CRASH PULSE (G'S-TIME)= 10 0.06 10 0.084 0 0.102 0 0.15

TIME	G G/S	V FPS	VV FPS	X IN	X1 IN	P PSIG	VOL CI	Q #/SEC	G6
====	=====	=====	======	====	=====	======	======	=======	==
.000	.00	17.00	17.000	17.000	.000	-.000	175	.000	.00
.005	.00	17.00	16.930	17.001	1.019	-.000	175	.000	.00
.010	.00	17.00	16.726	17.011	2.029	-.000	175	.000	.00
.015	.00	17.00	16.385	17.037	3.023	-.000	175	.000	.00
.020	.00	17.00	15.916	17.087	3.993	-.000	175	.000	.00
.025	.00	17.00	15.309	17.170	4.930	-.000	175	.000	.00
.030	.00	17.00	14.569	17.293	5.827	-.000	175	.000	.00
.035	.00	17.00	13.694	17.464	6.676	-.000	175	.000	.00
.040	.00	17.00	12.685	17.692	7.466	-.000	175	.000	.00
.045	.00	17.00	11.542	17.985	8.195	-.000	175	.000	.00
.050	.00	17.00	10.265	18.350	8.850	-.000	175	.000	.00
.051	.00	17.00	9.993	18.432	8.972	-.000	175	.000	.00
.052	.00	17.00	9.716	18.518	9.090	.979	175	.000	.00
.053	.00	17.00	9.434	18.607	9.205	3.589	175	.000	.00
.054	.00	17.00	9.146	18.700	9.316	7.761	176	.000	.00
.055	.00	17.00	8.853	18.796	9.424	12.756	180	.000	.00
.056	.00	17.00	8.555	18.895	9.529	15.194	201	.000	-30.47
.057	-10.15	16.92	8.251	18.998	9.630	13.541	250	.000	*-305.46
.058	-27.42	16.36	7.942	19.101	9.727	10.986	320	.000	*-220.06
.059	-33.87	15.35	7.628	19.198	9.820	9.225	401	.000	55.02
.060	-27.16	14.32	7.309	19.288	9.910	7.970	495	.000	267.22
.061	-15.11	13.61	6.986	19.368	9.996	6.050	622	.000	142.41
.062	-10.04	13.20	6.664	19.447	10.078	3.270	809	.000	21.35
.063	-5.13	12.99	6.342	19.525	10.156	.555	1066	.000	*-116.27

.064	-13.57	12.80	6.020	19.606	10.230	1.460	1165	.000	*-113.4
.065	-31.42	12.11	5.698	19.646	10.300	4.497	1194	.000	3.64
.066	-41.67	10.95	5.376	19.755	10.367	5.960	1284	.000	-46.61
.067	-47.56	9.52	5.054	19.818	10.429	4.778	1504	.000	*-206.32
.068	-47.67	7.96	4.732	19.865	10.488	2.303	1852	.000	*-171.14
.069	-32.92	6.57	4.410	19.897	10.543	.383	2239	.000	182.47
.070	-20.60	5.80	4.088	19.919	10.594	1.420	2317	4.733	214.91
.071	-19.56	5.14	3.766	19.938	10.641	1.890	2309	5.350	30.66
.075	.00	4.75	2.478	20.018	10.791	-.059	3287	.000	.00
.080	-14.16	3.57	.866	20.180	10.691	2.225	3404	5.508	-14.16
.085	-19.10	.84	-.731	20.313	10.695	3.001	3389	6.286	-19.10
.090	-21.06	-2.41	-2.019	20.352	10.810	3.310	3385	6.566	-21.06
.095	-22.00	-5.88	-2.860	20.253	10.661	3.457	3396	6.695	-22.00
.100	-21.62	-9.44	-3.254	19.978	10.476	3.397	3426	6.643	-21.62
.105	-18.36	-12.69	-3.286	19.509	10.279	2.886	3477	6.171	-18.36
.110	-14.30	-15.33	-3.286	18.862	10.082	2.247	3549	5.504	-14.30
.115	-10.45	-17.33	-3.286	18.076	9.885	1.642	3635	4.762	-10.45
.120	-7.17	-18.75	-3.286	17.188	9.687	1.126	3733	3.999	-7.17
.125	-4.53	-19.69	-3.286	16.230	9.490	.711	3838	3.234	-4.53
.130	-2.51	-20.26	-3.286	15.227	9.293	.394	3949	2.473	-2.51

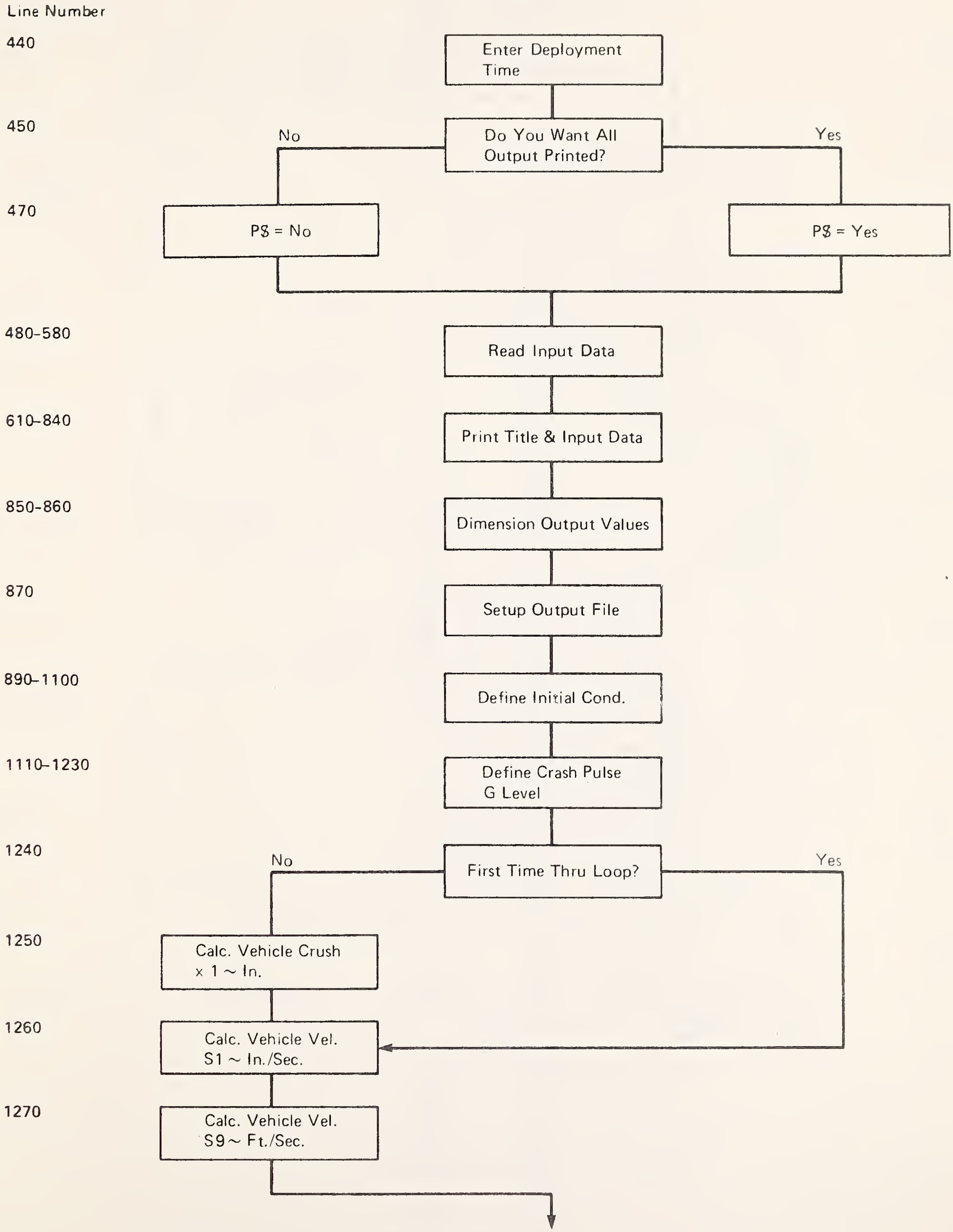
TIME ====	B G'S =====	BV FPS ======	BD IN ======	CSV FPS =======	CSD IN ======	CSF LB ======	DS IN ======	PD IN ======	PF LB ====
.000	0.	17.	.00	17.00	.00	0.	.00	.00	0.
.005	-1.	17.	1.02	17.00	1.02	0.	.00	1.02	0.
.010	-2.	17.	2.03	17.00	2.04	0.	.00	2.04	0.
.015	-3.	16.	3.02	17.00	3.06	0.	.00	3.06	0.
.020	-3.	16.	3.99	17.00	4.08	0.	.00	4.08	0.
.025	-4.	15.	4.93	17.00	5.10	0.	.00	5.10	0.
.030	-5.	15.	5.83	17.00	6.12	0.	.00	6.12	0.
.035	-6.	14.	6.68	17.00	7.14	0.	.00	7.14	0.
.040	-7.	13.	7.47	17.00	8.16	0.	.00	8.16	0.
.045	-8.	12.	8.20	17.00	9.18	0.	.00	9.18	0.
.050	-8.	10.	8.85	17.00	10.20	0.	.00	10.20	0.
.051	-9.	10.	8.97	17.00	10.40	0.	.00	10.40	0.
.052	-75.	9.	9.09	17.00	10.61	0.	.00	10.61	0.
.053	-277.	5.	9.18	17.00	10.81	0.	.03	10.81	0.
.054	-598.	-8.	9.17	17.00	11.02	0.	.15	11.02	0.
.055	-993.	-32.	8.94	17.00	11.22	0.	.49	11.22	0.
.056	-463.	-63.	8.35	17.00	11.42	30.	1.18	11.42	0.
.057	1143.	-58.	7.57	11.55	11.61	414.	2.01	11.63	162.
.058	2070.	-6.	7.16	2.05	11.68	612.	2.87	11.83	439.
.059	1304.	56.	7.46	-1.66	11.68	481.	3.79	12.02	534.
.060	-685.	73.	8.31	3.36	11.68	148.	4.79	12.20	365.
.061	-1518.	33.	8.98	11.58	11.77	0.	5.92	12.36	102.
.062	-1061.	-11.	9.10	14.16	11.93	0.	7.21	12.52	13.
.063	608.	-31.	8.80	13.69	12.10	122.	8.63	12.68	19.
.064	1058.	7.	8.63	9.12	12.24	244.	9.22	12.84	152.
.065	-696.	19.	8.84	7.07	12.33	196.	9.32	12.99	197.
.066	-1404.	-18.	8.88	7.06	12.42	216.	9.76	13.12	166.
.067	440.	-45.	8.45	3.43	12.49	416.	10.72	13.25	236.

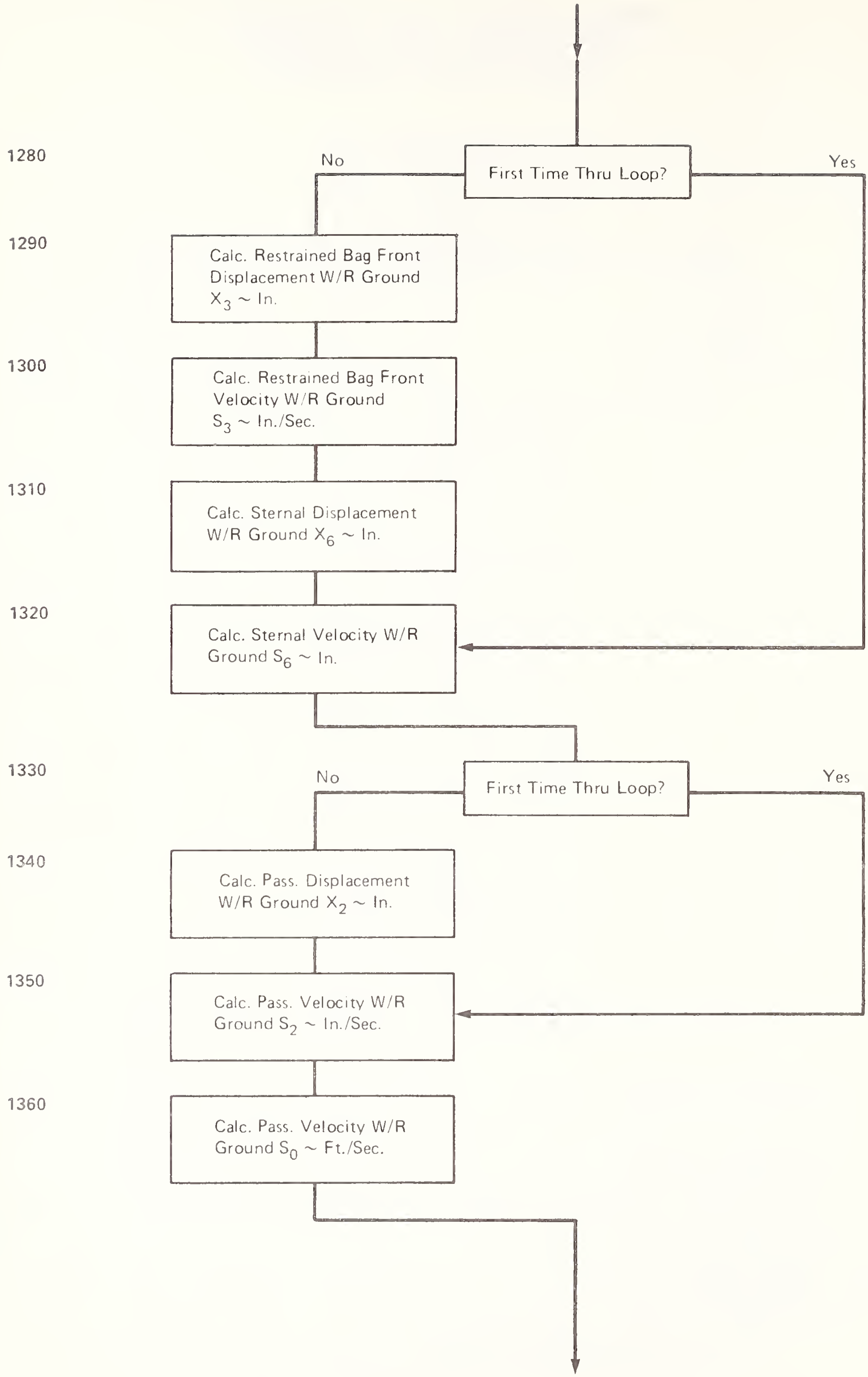
.063	3941.	4.	8.12	-3.62	12.49	547.	12.23	13.35	408.
.067	3143.	101.	8.76	-5.16	12.42	265.	14.12	13.44	428.
.070	-1433.	116.	10.20	4.12	12.41	0.	14.95	13.51	160.
.071	-2064.	56.	11.25	8.12	12.49	0.	15.29	13.58	14.
.075	0.	5.	10.81	4.75	13.81	0.	19.40	13.81	0.
.080	-14.	4.	11.07	3.57	14.07	0.	20.00	14.07	0.
.085	-19.	1.	11.21	.84	14.21	0.	20.00	14.21	0.
.090	-21.	-2.	11.16	-2.41	14.16	0.	20.00	14.16	0.
.095	-22.	-6.	10.91	-5.88	13.91	0.	20.00	13.91	0.
.100	-22.	-9.	10.45	-9.44	13.45	0.	20.00	13.45	0.
.105	-13.	-13.	9.79	-12.69	12.79	0.	20.00	12.79	0.
.110	-14.	-15.	8.94	-15.33	11.94	0.	20.00	11.94	0.
.115	-10.	-17.	7.96	-17.33	10.96	0.	20.00	10.96	0.
.120	-7.	-19.	6.88	-18.75	9.88	0.	20.00	9.88	0.
.125	-5.	-20.	5.72	-19.69	8.72	0.	20.00	8.72	0.
.130	-3.	-20.	4.52	-20.26	7.52	0.	20.00	7.52	0.

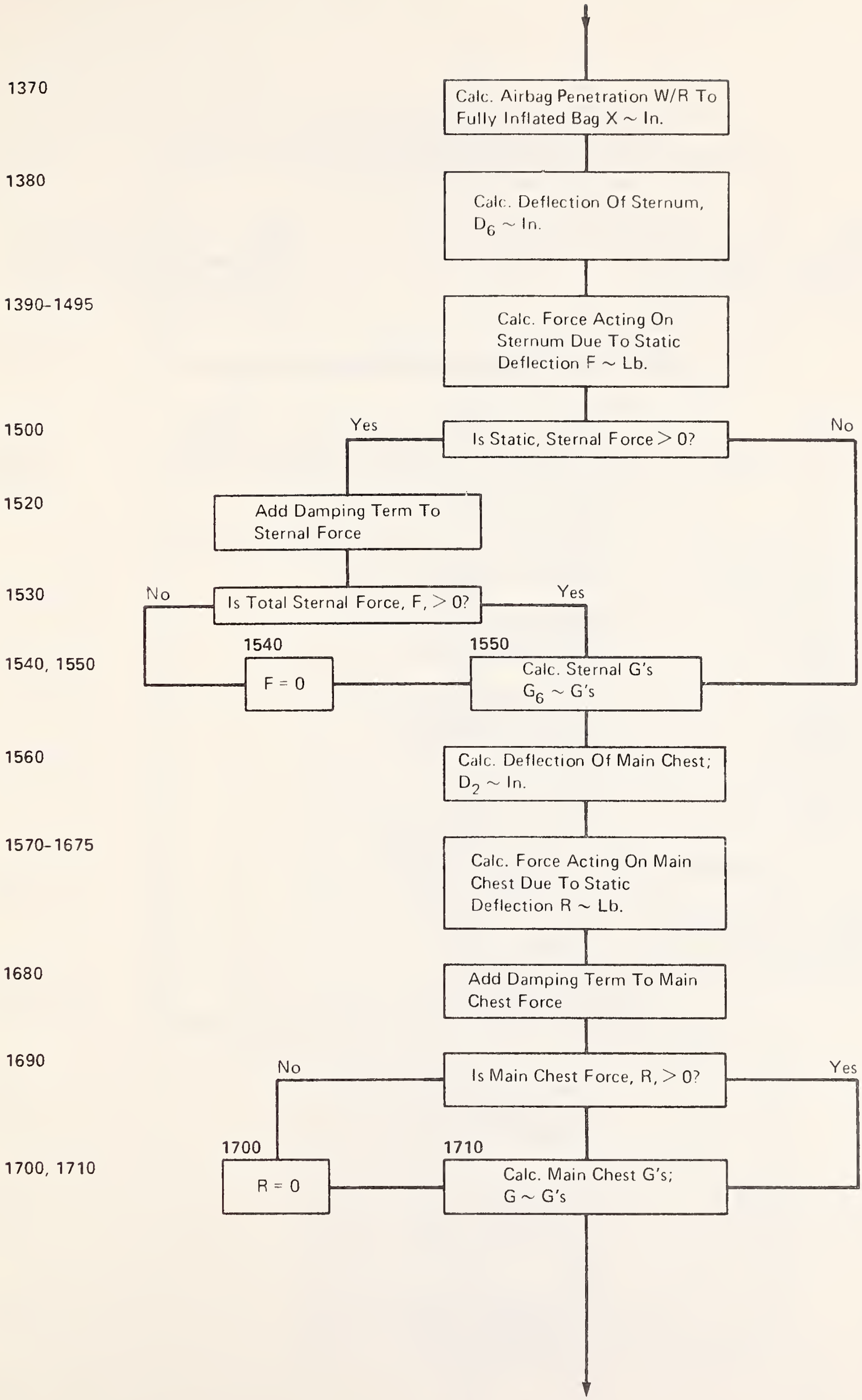
APPENDIX C

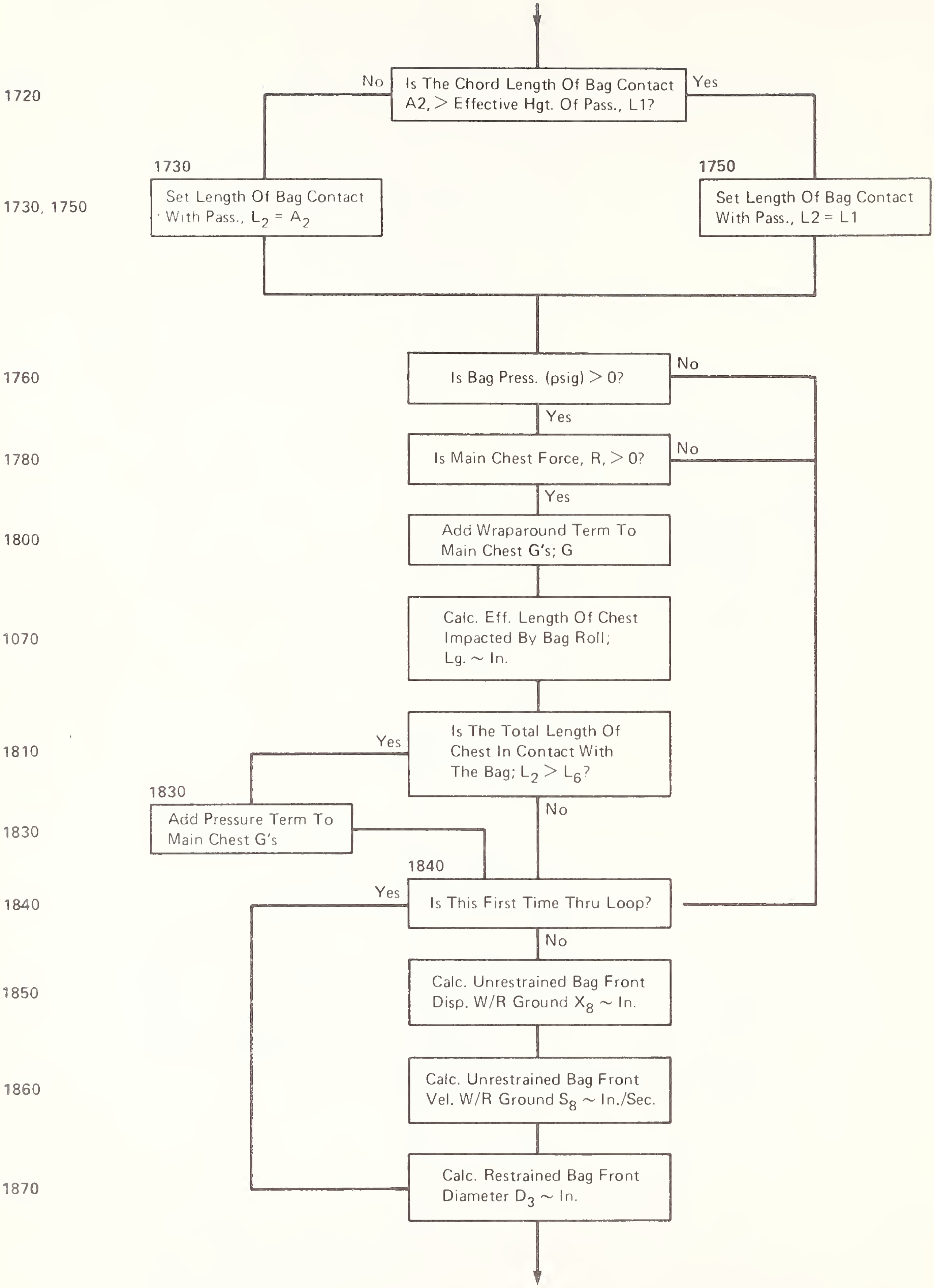
DEPLOY FLOWCHARTS

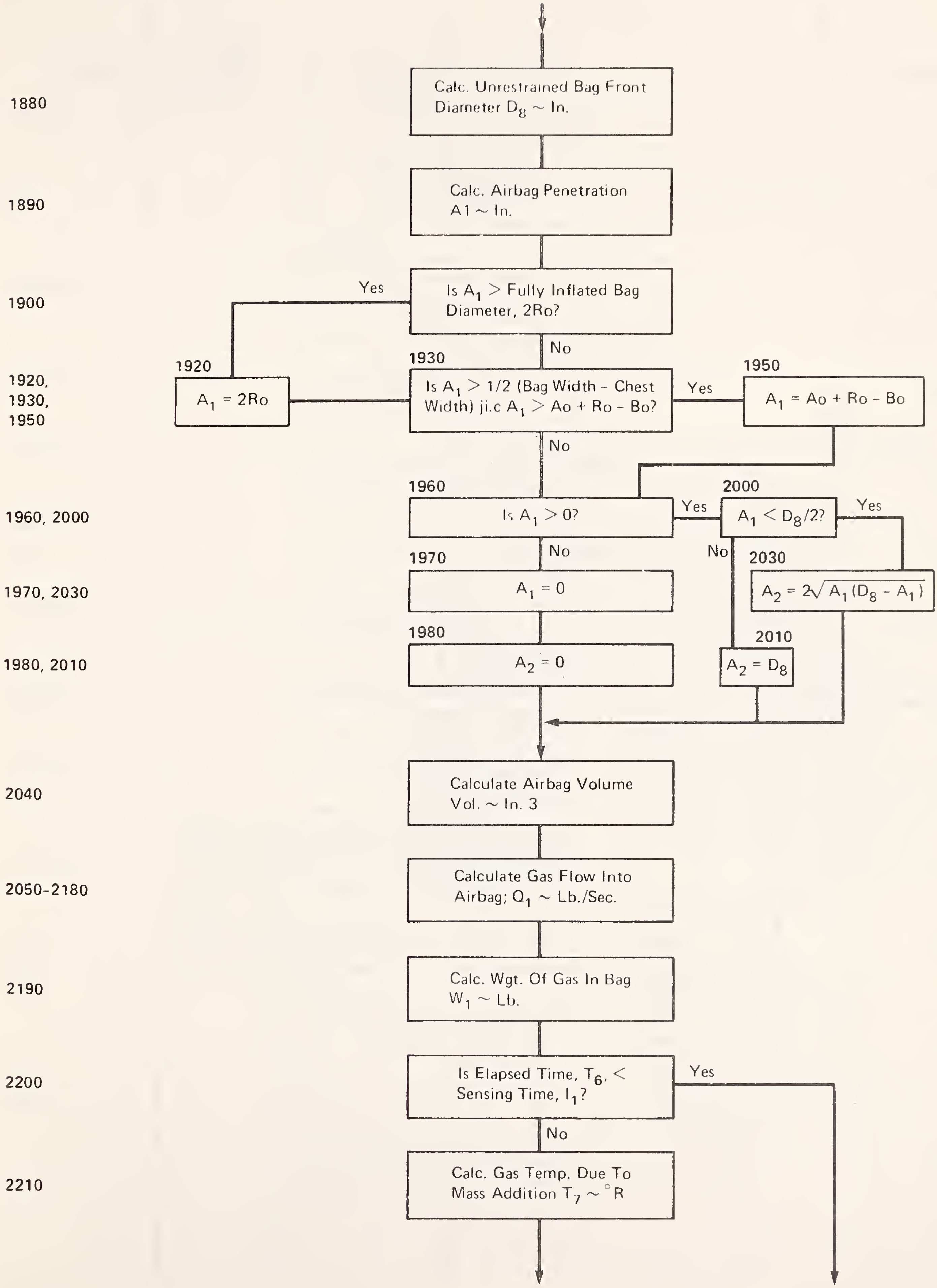
Flow Chart for "Deploy" Computer Program

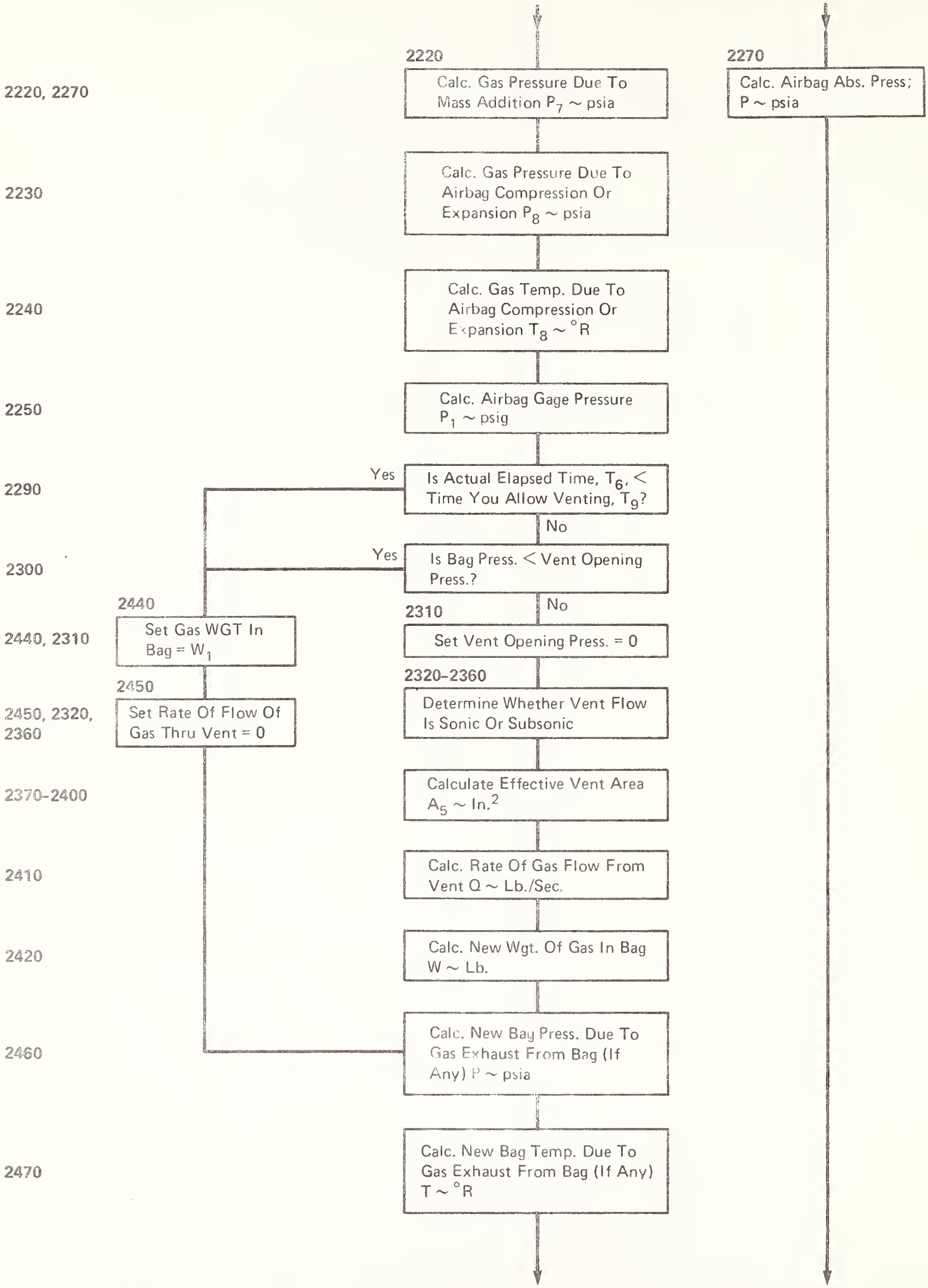



1280
No
First Time Thru Loop?
Yes
1290
Calc. Restrained Bag Front Displacement W/R Ground X_3 ~ In.
1300
Calc. Restrained Bag Front Velocity W/R Ground S_3 ~ In./Sec.
1310
Calc. Sternal Displacement W/R Ground X_6 ~ In.
1320
Calc. Sternal Velocity W/R Ground S_6 ~ In.
1330
No
First Time Thru Loop?
Yes
1340
Calc. Pass. Displacement W/R Ground X_2 ~ In.
1350
Calc. Pass. Velocity W/R Ground S_2 ~ In./Sec.
1360
Calc. Pass. Velocity W/R Ground S_0 ~ Ft./Sec.


1370
Calc. Airbag Penetration W/R To Fully Inflated Bag X ~ In.
1380
Calc. Deflection Of Sternum, D_6 ~ In.
1390-1495
Calc. Force Acting On Sternum Due To Static Deflection F ~ Lb.
1500
Is Static, Sternal Force > 0?
Yes
No
1520
Add Damping Term To Sternal Force
1530
Is Total Sternal Force, F, > 0?
No
Yes
1540, 1550
1540
F = 0
1550
Calc. Sternal G's G_6 ~ G's
1560
Calc. Deflection Of Main Chest; D_2 ~ In.
1570-1675
Calc. Force Acting On Main Chest Due To Static Deflection R ~ Lb.
1680
Add Damping Term To Main Chest Force
1690
Is Main Chest Force, R, > 0?
No
Yes
1700, 1710
1700
R = 0
1710
Calc. Main Chest G's; G ~ G's


1720
No
Is The Chord Length Of Bag Contact A2, > Effective Hgt. Of Pass., L1?
Yes
1730, 1750
1730
Set Length Of Bag Contact With Pass., $L_2 = A_2$
1750
Set Length Of Bag Contact With Pass., L2 = L1
1760
Is Bag Press. (psig) > 0?
No
Yes
1780
Is Main Chest Force, R, > 0?
No
Yes
1800
Add Wraparound Term To Main Chest G's; G
1070
Calc. Eff. Length Of Chest Impacted By Bag Roll; Lg. ~ In.
1810
Yes
Is The Total Length Of Chest In Contact With The Bag; $L_2 > L_6$?
1830
1830
Add Pressure Term To Main Chest G's
No
1840
1840
Yes
Is This First Time Thru Loop?
No
1850
Calc. Unrestrained Bag Front Disp. W/R Ground X_8 ~ In.
1860
Calc. Unrestrained Bag Front Vel. W/R Ground S_8 ~ In./Sec.
1870
Calc. Restrained Bag Front Diameter D_3 ~ In.


1880
Calc. Unrestrained Bag Front Diameter $D_8 \sim$ In.
1890
Calc. Airbag Penetration A1 ~ In.
1900
Is $A_1 >$ Fully Inflated Bag Diameter, 2Ro?
Yes
No
1920, 1930, 1950
1920
$A_1 = 2Ro$
1930
Is $A_1 > 1/2$ (Bag Width - Chest Width) ji.c $A_1 > Ao + Ro - Bo$?
Yes
1950
$A_1 = Ao + Ro - Bo$
No
1960, 2000
1960
Is $A_1 > 0$?
Yes
2000
$A_1 < D_8/2$?
Yes
No
No
1970, 2030
1970
$A_1 = 0$
2030
$A_2 = 2\sqrt{A_1 (D_8 - A_1)}$
1980, 2010
1980
$A_2 = 0$
2010
$A_2 = D_8$
2040
Calculate Airbag Volume Vol. ~ In. 3
2050-2180
Calculate Gas Flow Into Airbag; $Q_1 \sim$ Lb./Sec.
2190
Calc. Wgt. Of Gas In Bag $W_1 \sim$ Lb.
2200
Is Elapsed Time, T_6, < Sensing Time, I_1?
Yes
No
2210
Calc. Gas Temp. Due To Mass Addition $T_7 \sim {}^\circ R$



2220, 2270
2220
Calc. Gas Pressure Due To Mass Addition $P_7 \sim$ psia
2270
Calc. Airbag Abs. Press; $P \sim$ psia
2230
Calc. Gas Pressure Due To Airbag Compression Or Expansion $P_8 \sim$ psia
2240
Calc. Gas Temp. Due To Airbag Compression Or Expansion $T_8 \sim {}^\circ R$
2250
Calc. Airbag Gage Pressure $P_1 \sim$ psig
2290
Is Actual Elapsed Time, T_6, < Time You Allow Venting, T_9?
Yes
No
2300
Is Bag Press. < Vent Opening Press.?
Yes
No
2440, 2310
2440
Set Gas WGT In Bag = W_1
2310
Set Vent Opening Press. = 0
2450, 2320, 2360
2450
Set Rate Of Flow Of Gas Thru Vent = 0
2320-2360
Determine Whether Vent Flow Is Sonic Or Subsonic
2370-2400
Calculate Effective Vent Area $A_5 \sim$ In.^{2}
2410
Calc. Rate Of Gas Flow From Vent $Q \sim$ Lb./Sec.
2420
Calc. New Wgt. Of Gas In Bag $W \sim$ Lb.
2460
Calc. New Bag Press. Due To Gas Exhaust From Bag (If Any) $P \sim$ psia
2470
Calc. New Bag Temp. Due To Gas Exhaust From Bag (If Any) $T \sim {}^\circ R$

2480–2520

2530

2540–2550

2660–2670

2580, 2950

2590, 2890, 2960

2600, 2900

2610, 2910, 2980

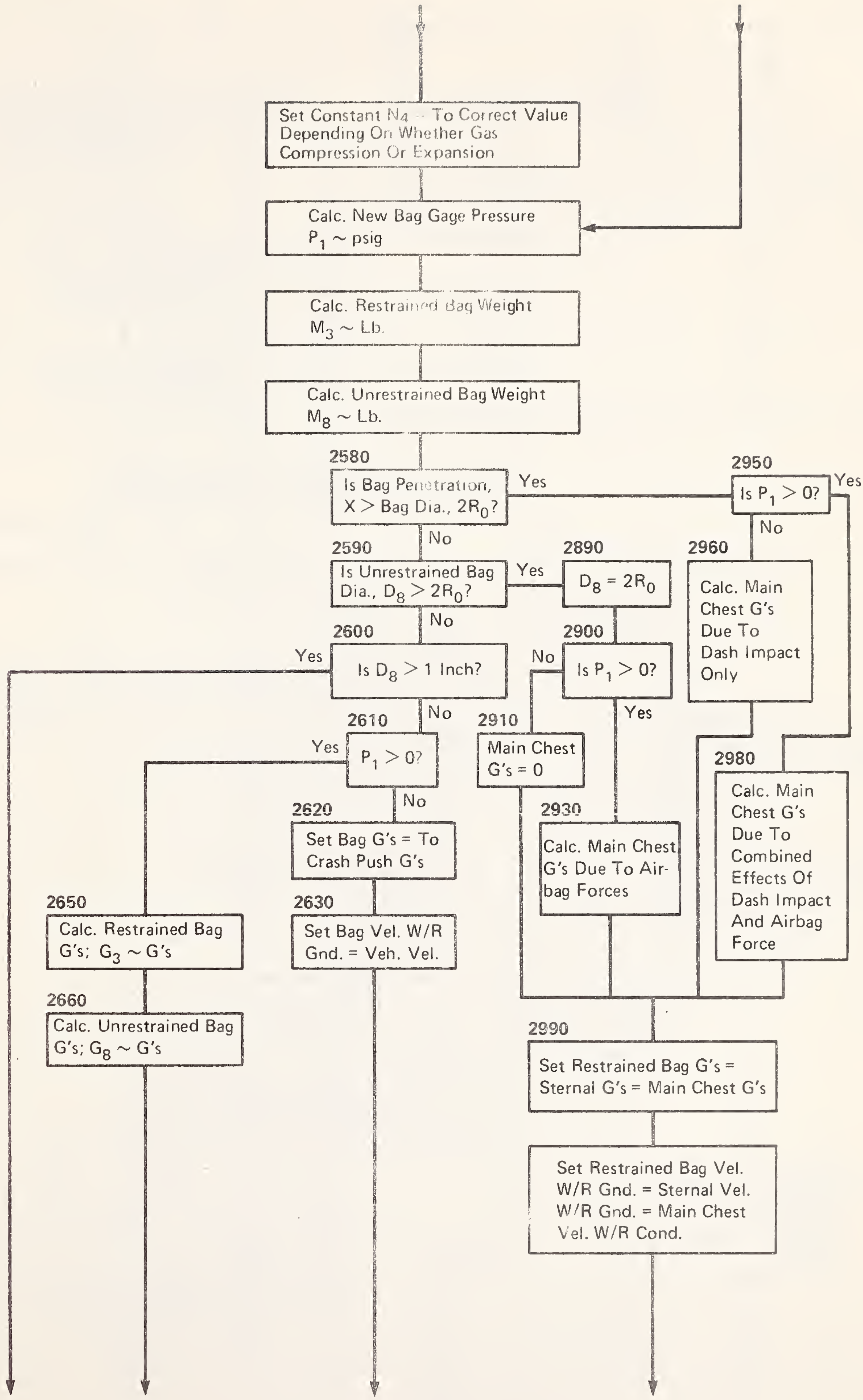
2620, 2930

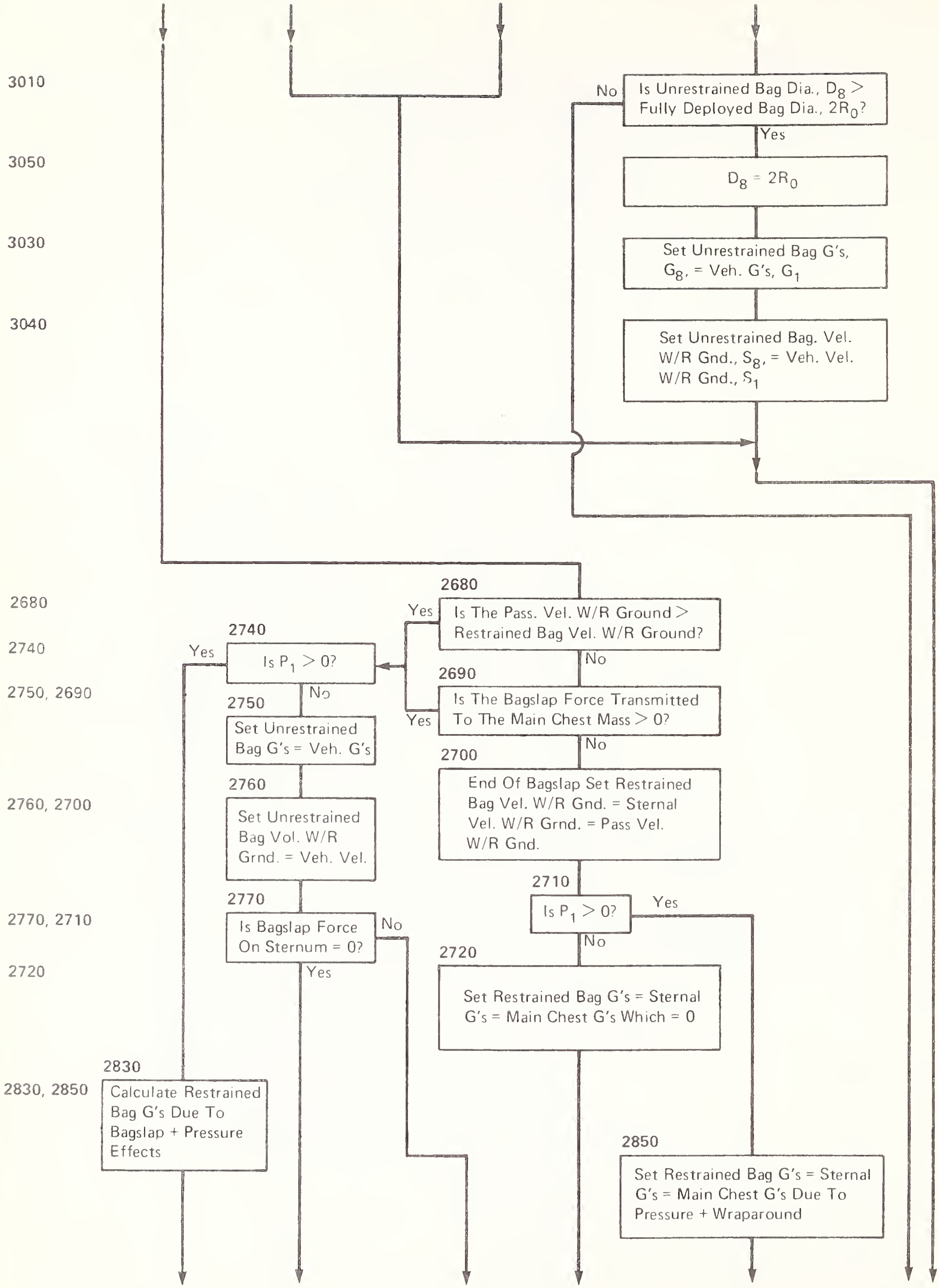
2650, 2630

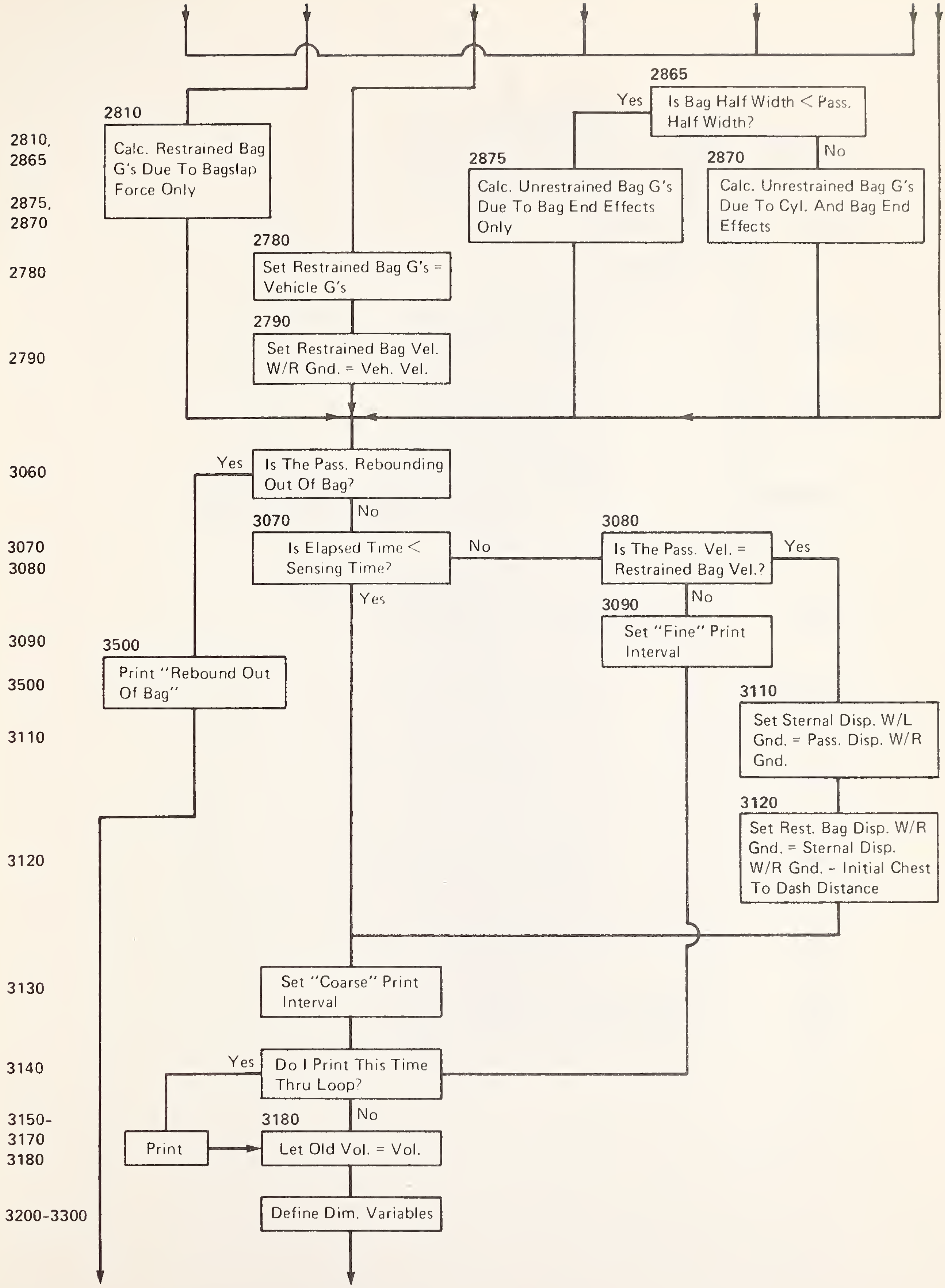
2660

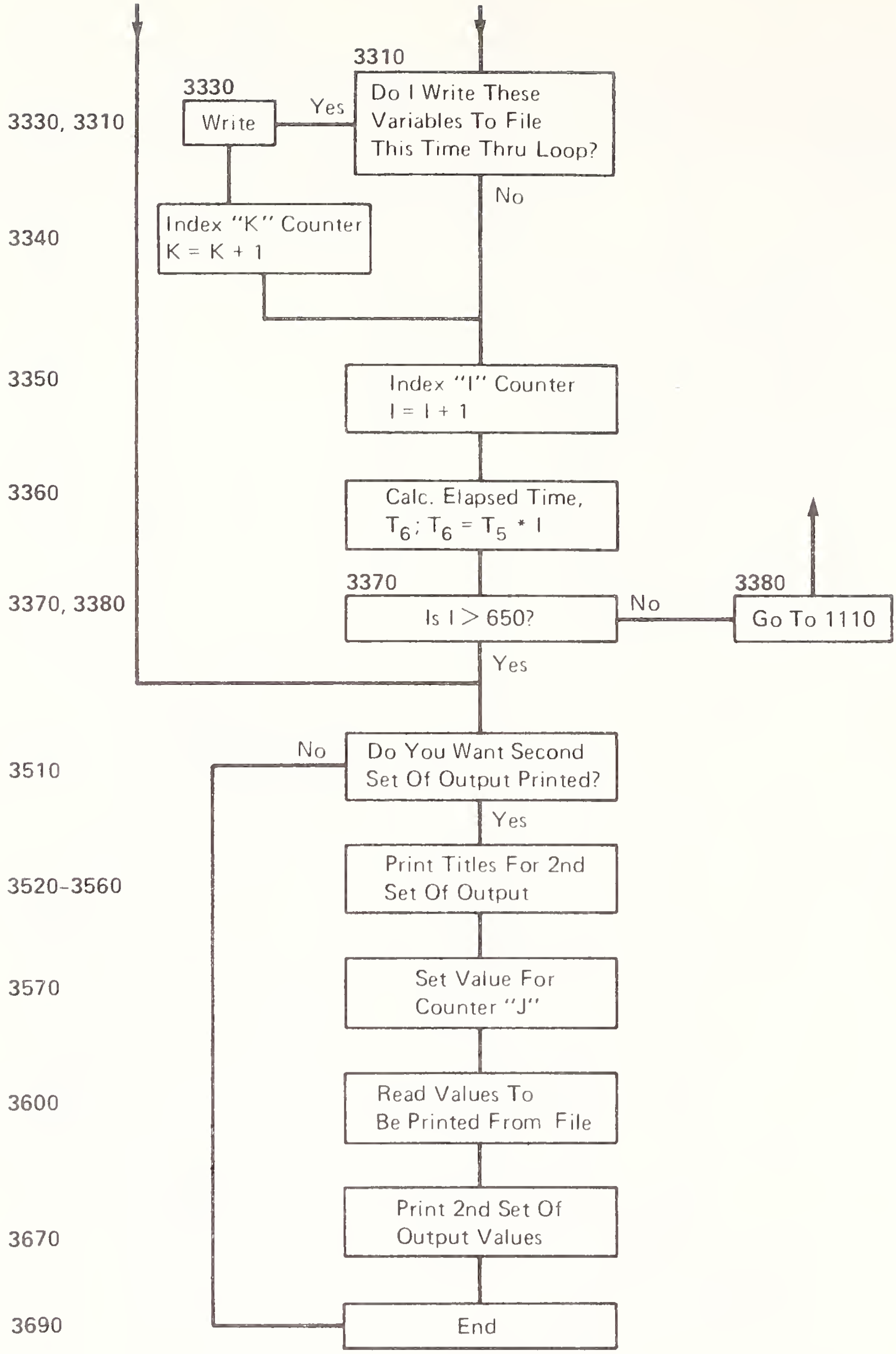
2990

3000




3010
3050
3030
3040
2680
2740
2750, 2690
2760, 2700
2770, 2710
2720
2830, 2850
No
Is Unrestrained Bag Dia., D_8 > Fully Deployed Bag Dia., $2R_0$?
Yes
$D_8 = 2R_0$
Set Unrestrained Bag G's, G_8, = Veh. G's, G_1
Set Unrestrained Bag. Vel. W/R Gnd., S_8, = Veh. Vel. W/R Gnd., S_1
2680
Yes
Is The Pass. Vel. W/R Ground > Restrained Bag Vel. W/R Ground?
No
2740
Yes
Is P_1 > 0?
No
2690
Is The Bagslap Force Transmitted To The Main Chest Mass > 0?
Yes
No
2750
Set Unrestrained Bag G's = Veh. G's
2700
End Of Bagslap Set Restrained Bag Vel. W/R Gnd. = Sternal Vel. W/R Grnd. = Pass Vel. W/R Gnd.
2760
Set Unrestrained Bag Vol. W/R Grnd. = Veh. Vel.
2770
Is Bagslap Force On Sternum = 0?
No
Yes
2710
Is P_1 > 0?
Yes
No
2720
Set Restrained Bag G's = Sternal G's = Main Chest G's Which = 0
2830
Calculate Restrained Bag G's Due To Bagslap + Pressure Effects
2850
Set Restrained Bag G's = Sternal G's = Main Chest G's Due To Pressure + Wraparound


2810,
2865
2875,
2870
2780
2790
3060
3070
3080
3090
3500
3110
3120
3130
3140
3150-
3170
3180
3200-3300
2810
Calc. Restrained Bag G's Due To Bagslap Force Only
2865
Is Bag Half Width < Pass. Half Width?
Yes
No
2875
Calc. Unrestrained Bag G's Due To Bag End Effects Only
2870
Calc. Unrestrained Bag G's Due To Cyl. And Bag End Effects
2780
Set Restrained Bag G's = Vehicle G's
2790
Set Restrained Bag Vel. W/R Gnd. = Veh. Vel.
Is The Pass. Rebounding Out Of Bag?
Yes
No
3070
Is Elapsed Time < Sensing Time?
No
Yes
3080
Is The Pass. Vel. = Restrained Bag Vel.?
Yes
No
3090
Set "Fine" Print Interval
3500
Print "Rebound Out Of Bag"
3110
Set Sternal Disp. W/L Gnd. = Pass. Disp. W/R Gnd.
3120
Set Rest. Bag Disp. W/R Gnd. = Sternal Disp. W/R Gnd. - Initial Chest To Dash Distance
Set "Coarse" Print Interval
Do I Print This Time Thru Loop?
Yes
No
3180
Print
Let Old Vol. = Vol.
Define Dim. Variables


3330, 3310
3340
3350
3360
3370, 3380
3510
3520-3560
3570
3600
3670
3690
3310
3330
Write
Yes
Do I Write These Variables To File This Time Thru Loop?
No
Index "K" Counter K = K + 1
Index "I" Counter I = I + 1
Calc. Elapsed Time, T_6; $T_6 = T_5 * I$
3370
Is I > 650?
No
3380
Go To 1110
Yes
No
Do You Want Second Set Of Output Printed?
Yes
Print Titles For 2nd Set Of Output
Set Value For Counter "J"
Read Values To Be Printed From File
Print 2nd Set Of Output Values
End

APPENDIX D

INPUT DATA FORMATS

Input Data Formats

Line 3090 U=5 Minimum Print Interval = 1 ms
U=1 Minimum Print Interval = 1/5 ms

Line 3390 DATA QO, I1, Q2, I2, Q3, I3, Q4, I4, Q5, I5

QO	=	lb/sec	First Data Point of Flow
I1	=	Time	Characteristic
Q2	=		Second Data Point
I2	=		
Q3	=		Third Data Point
I3	=		
Q4	=		Fourth Data Point
I4	=		
Q5	=		Fifth Data Point
I5	=		

The First Data Point must include sensing time.

Line 3400 DATA RO, AO, L1 B1

RO = Bag Radius (in.)
AO = Bag Half Cylinder Length (in.)
L1 = Effective Height of Passenger (in.)
B1 = Vent Coefficient

Line 3410 DATA A6, P2, N1, N2, N3

A5 = Vent Area (in^2)
P2 = Pressure Vent Opens at (psig)
N1 = Polytropic Process Exponents (Flow)
N2 = Polytropic Process Exponents (Compression)
N3 = Polytropic Process Exponents (Exhaust)

Line 3420 DATA C1, C2, T5

C1 = Vent Discharge Coefficient, Subsonic
C2 = Vent Discharge Coefficient, Sonic
T5 = Integration Interval (sec.)

Line 3430 DATA PO, TO, R9

PO = Initial Bag Pressure
TO = Gas Temperature (^{O}R)
R9 = Universal Gas Constant

Line 3440 DATA WO, W6, SO, BO

WO = Passenger Weight (lbs.)
W6 = Chest Sternal Weight (lbs.)
SO = Impact Velocity (fps)
BO = Half Chest Width (in.)

Line 3450 DATA B2, W2, B3, W3, B4, W4, B5, W5

B2 =	G's	First Data Point of Crash Pulse
W2 =	Time	
B3 =		Second Data Point
W3 =		
B4 =		Third Data Point
W4 =		
B5 =		Fourth Data Point
W5 =		

Line 3460 DATA C6, P9

C6 = Initial Distance from Dash (in.)
P9 = Dash Padding Stiffness (G's/in.)

Line 3470 DATA N6, X9, L9, D9, D4

N6 = Passenger Mass Factor During Bagslap
X9 = Manifold Sock Dia. (in.)
L9 = Manifold Sock Length (in.)
D9 = Sternum Damping Coefficient
D4 = Main Chest Damping Coefficient

Line 3480 DATA Fl, Ul, F2, U2, F3, U3, F4, U4

Fl =	lbs	First Data Point of Sternum Force vs. Displacement Curve
Ul =	in.	
F2 =		Second Data Point
U2 =		
F3 =		Third Data Point
U3 =		
F4 =		Fourth Data Point
U4 =		

Line 3440 DATA WO, W6, SO, BO

WO	=	Passenger Weight (lbs.)	
W6	=	Chest Sternal Weight (lbs.)	
SO	=	Impact Velocity (fps)	
BO	=	Half Chest Width (in.)	

Line 3450 DATA B2, W2, B3, W3, B4, W4, B5, W5

B2	=	G's	First Data Point of
W2	=	Time	Crash Pulse
B3	=		Second Data Point
W3	=		
B4	=		Third Data Point
W4	=		
B5	=		Fourth Data Point
W5	=		

Line 3460 DATA C6, P9

C6	=	Initial Distance from Dash (in.)	
P9	=	Dash Padding Stiffness (G's/in.)	

Line 3470 DATA N6, X9, L9, D9, D4

N6	=	Passenger Mass Factor During Bagslap	
X9	=	Manifold Sock Dia. (in.)	
L9	=	Manifold Sock Length (in.)	
D9	=	Sternum Damping Coefficient	
D4	=	Main Chest Damping Coefficient	

Line 3480 DATA F1, U1, F2, U2, F3, U3, F4, U4

F1	=	lbs	First Data Point of Sternum
U1	=	in.	Force vs. Displacement Curve
F2	=		Second Data Point
U2	=		
F3	=		Third Data Point
U3	=		
F4	=		Fourth Data Point
U4	=		

Line 3490 DATA M6, R1, V1, R2, V2, R3, V3, R4, V4

M6 = Bag Material Weight (oz./sq. yd.)

R1 = lbs.   First Data Point of Chest
V1 = in.   Force vs. Displacement Curve

R2 =   Second Data Point
V2 =

R3 =   Third Data Point
V3 =

R4 =   Fourth Data Point
V4 =